UNIT-6
Refrigeration

**Definition**
Refrigeration is the process of providing and maintaining temperature of the system below that of the surrounding atmosphere.

**Carnot Cycle**
The reversed carnot cycle can be considered in refrigeration system.

\[
C.O.P = \frac{T_2}{T_2 - T_1} \quad \text{where} \quad T_2 < T_1
\]

Unit of Refrigeration
The common unit used in the field of refrigeration is known as Ton of refrigeration.
A ton of refrigeration is defined as the quantity of heat required to be removed to produce one ton (1000kg) of ice within 24 hours when the initial condition of water is 0°C

\[
Ton \text{ of refrigeration} = \frac{1000 \times 335}{24 \times 3600} = 3.5 \text{ kJ/s}
\]

Consider a refrigerator of T tons capacity,
Refrigeration capacity = 3.5 kJ/s
Heat removed from refrigerator = Refrigeration effect = R.E. kJ/s
Power of the compressor = work/kg of refrigerant x mass flow rate

**Air Refrigeration system working on**
**Bell-coleman cycle**

In air refrigeration system, air is used as the refrigerant which always remains in the gaseous phase. The heat removed consists only of sensible heat and as a result, the coefficient of performance (C.O.P) is low.
The various processes are:
Process 1-2:  
The air leaving the evaporator enters a compressor. Where it is compressed isentropically to higher pressure and temperature.  

Process 2-3:  
This high pressure, high temperature air, then enters a cooler where it is cooled at constant pressure to a low temperature.  

Process 3-4: This high pressure, low temperature air is then expanded in an expander to lower pressure and temperature in a isentropic manner. At point 4, the temperature of the air will be lowest.  

Process 4-1: This low temperature air is then passed through the heater coils where it absorbs heat from the space to be cooled namely the refrigerator and the air gets heated back to the initial temperature, but in the process, it cools the refrigerator. And the cycle repeats.

Air refrigeration system

Expression C.O.P when compression and expansion are Isentropic
Refrigeration Effect = Heat removed from the refrigerator

\[ C_O.P = C_p (T_i - T_d) \text{kJ/kg} \]

Work input = \[ W_C - W_E = \gamma \left( \frac{P_2 V_2 - P_1 V_1}{\gamma - 1} \right) - \gamma \left( \frac{P_3 V_3 - P_4 V_4}{\gamma - 1} \right) \]

Work input = \[ W_C - W_E = \left( \frac{\gamma R}{\gamma - 1} \right) \left[ R(T_2 - T_1) - R(T_3 - T_4) \right] \]

\[ W_{net} = \left( \frac{\gamma R}{\gamma - 1} \right) \left[ (T_2 - T_1) - (T_3 - T_4) \right] \]

But \[ C_p = \frac{\gamma R}{\gamma - 1} \]

\[ W_{net} = C_p \left[ (T_2 - T_1) - (T_3 - T_4) \right] \]
Process 1-2 is isentropic

\[ \frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \quad \text{-----(2)} \]

Process 3-4 is isentropic

\[ \frac{T_3}{T_4} = \left( \frac{P_3}{P_4} \right)^{\frac{\gamma-1}{\gamma}} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \quad \text{-----(3)} \]

From (2) and (3)

\[ \frac{T_2}{T_1} = \frac{T_3}{T_4} \]

\[ \text{C.O.P} = \frac{RE}{\text{Work}} = \frac{C_p (T_1 - T_4)}{C_p [(T_2 - T_1) - (T_3 - T_4)]} \]

\[ \text{C.O.P} = \frac{(T_1 - T_4)}{[(T_2 - T_1) - (T_3 - T_4)]]} = \frac{1}{T_2 - T_3 - 1} \quad \text{-----(1)} \]

\[ \frac{T_2}{T_3} = \frac{T_1}{T_4} \]

\[ \frac{T_2 - 1}{T_3} = \frac{T_1 - 1}{T_4} \]

\[ \frac{T_2 - T_3}{T_3} = \frac{T_1 - T_4}{T_4} \]

\[ \frac{T_2 - T_3}{T_1 - T_4} = \frac{T_3}{T_4} \quad \text{-----(4)} \]

From (1) and (4)

\[ \text{C.O.P} = \frac{1}{\frac{T_3}{T_4} - 1} \]

\[ \text{C.O.P} = \frac{T_4}{\frac{T_3}{T_4} - 1} \]
Advantages of air refrigeration system

1. Air is cheap, easily available.
2. It is not flammable.
3. For a given capacity, weight of air refrigeration system is less compared to other system and hence it is widely used for aircraft cooling.

Disadvantages

1. Since heat removed by air consists only of sensible heat, weight of air required is high.
2. C.O.P of the system is low compared to other systems.

Problem 1

A cold storage is to be maintained at -5°C (268k) while the surroundings are at 35°C. The heat leakage from the surroundings into the cold storage is estimated to be 29kW. The actual C.O.P of the refrigeration plant is one third of an ideal plant working between the same temperatures. Find the power required to drive the plant. (VTU Jan 2007)

Solution:

\[ \text{C.O.P ideal} = \frac{T_2}{T_1 - T_2} \]

\[ = \frac{268}{308 - 268} = 6.7 \]
\[ Actual\ C.O.P = \frac{1}{3} \times ideal\ C.O.P \]
\[ = \frac{1}{3} \times 6.7 = 2.233 \]

Q2 = The heat removed from low temperature reservoir (cold storage) must be equal to heat leakage from surroundings to the cold storage (which is 29kW)

\[ Q_2 = 29kW \]

\[ Actual\ C.O.P = \frac{Q_2}{W} \]
\[ W = \frac{Q_2}{Actual\ C.O.P} = \frac{29}{2.233} \]

Power required = 12.98 kW

Problem 2
A refrigeration machine of 6 tones capacity working on Bell Coleman cycle has an upper limit pressure of 5.2 bar. The pressure and temperature at the start of the compression are 1 bar and 18°C respectively. The cooled compressed air enters the expander at 41°C, assuming both expansion and compression to be adiabatic with an index of 1.4.

Calculate:-
(i) Co-efficient of performance.
(ii) Quantity of air circulated per minute.
(iii) Piston displacement of compressor and expander
(iv) Bore of compression and expansion cylinder when the unit runs at 240 rpm and is double acting with stroke length = 200 mm
(v) Power required to drive the unit

Solution :-
\[ T_1 = 18°C \quad P_1 = 1\text{bar} \]
\[ T_3 = 41°C \quad P_2 = 5.2\text{bar} \]
Work input = \( C_p \left( (T_2 - T_1) - (T_3 - T_4) \right) \)
= 1.005\((466 - 291) - (314 - 196)\) = 57kJ / kg

C.O.P = \( \frac{\text{Reigeration effect}}{\text{Work input}} \)
= \( \frac{95.42}{57} \) = 1.67

Re frigeration capacity = 6 tons = 6x3.5 = 21kJ/s

Mass of air/sec = \( \frac{\text{Reigeration capacity}}{\text{R.E}} \)
= \( \frac{21}{95.42} \) = 0.22kg / s

Power required = \( \text{workdone}/\text{kg of air} \times \text{Mass of air/sec} \)
= 57 x 0.22 = 12.54kW

Mass of air/min = 0.22x60 = 13.2kg/min

\[ V_1 = \frac{mRT_1}{P_1} = \frac{13.2 \times 0.287 \times 291}{1 \times 10^2} = 11m^3 / \text{min} \]

Piston displacement of compressor\( V_1 = 11m^3 / \text{min} \)

\[ V_4 = \frac{mRT_4}{P_4} = \frac{13.2 \times 0.287 \times 196}{1 \times 10^2} = 7.42m^3 / \text{min} \]

Piston displacement of expander \( V_4 = 7.42m^3 / \text{min} \)

But \( V_1 = 2 \frac{\pi}{4} d_1^2 LN \)

\[ 11 = 2 \frac{\pi}{4} d_1^2 \times 0.2 \times 240 \]

\( d_1 = \text{diameter of compressor cylinder} = 0.38\text{m} = 38\text{cm} \)

\[ V_4 = 2 \frac{\pi}{4} d_2^2 LN \]

\[ 7.42 = 2 \frac{\pi}{4} d_2^2 \times 0.2 \times 240 \]

\( d_2 = \text{diameter of expander cylinder} = 0.313\text{m} = 31.3\text{cm} \)
**Problem 3**  An air refrigerator system operating on Bell Coleman cycle, takes in air from cold room at 268 K and compresses it from 1 bar to 5.5 bar the index of compression being 1.25. the compressed air is cooled to 300 K, the ambient temperature is 20°C. Air expands in expander where the index of expansion is 1.35.

**Calculate:**

i)  **C.O.P of the system**

ii)  **Quantity of air circulated per minute for production of 1500 kg of ice per day at 0°C from water at 20°C.**

iii)  **Capacity of the plant.**

**Solution**

\[
T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} = 268 \left( \frac{5.5}{1} \right)^{\frac{1.25 - 1}{1.25}} = 376.8 \text{K}
\]

\[
T_4 = T_3 \left( \frac{P_3}{P_4} \right)^{\frac{\gamma - 1}{\gamma}} = 300 \left( \frac{1}{5.5} \right)^{\frac{1.35 - 1}{1.35}} = 192.83 \text{K}
\]

\[
W_C = \frac{n}{n-1} \left( \frac{\gamma - 1}{\gamma} \right) C_p (T_2 - T_1)
= \left( \frac{1.25}{1.25 - 1} \right) \left( 1.4 - 1 \right) 1.005(376.8 - 268) = 156.2 \text{kJ/kg}
\]

\[
W_E = \frac{n}{n-1} \left( \frac{\gamma - 1}{\gamma} \right) C_p (T_3 - T_4)
= \left( \frac{1.35}{1.35 - 1} \right) \left( 1.4 - 1 \right) 1.005(300 - 192.83) = 118.69 \text{kJ/kg}
\]

\[
\text{Network} = W_C - W_E = 156.2 - 118.69 = 37.5 \text{kJ/kg}
\]

\[
R.E = C_p (T_1 - T_4) = 1.005(268 - 192.83) = 75.54 \text{kJ/kg}
\]

\[
\text{C.O.P} = \frac{R.E}{\text{work}} = \frac{75.54}{37.5} = 2
\]
Problem 4
An air refrigeration system is to be designed according to the following specifications
Pressure of air at compressor inlet=101kPa
Pressure of work at compressor outlet=404kPa
Pressure loss in the inter cooler=12kPa
Pressure loss in the cold chamber=3kPa
Temperature of air at compressor inlet=7°
Temperature of air at turbine inlet=27°
Isentropic efficiency of compressor =85%
Isentropic efficiency of turbine =85%
Determine
i) C.O.P of cycle
ii) Power required to produce 1 ton of refrigeration
iii) Mass flow rate of air required for 1 ton of refrigeration

Solution :-
\[ T_1 = -7°C \quad P_1 = 101kPa \]
\[ T_3 = 27°C \eta_T = 0.85; \eta_C = 0.85 \]

Process 1-2 is isentropic, Hence
\[ T_2' = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \]
\[ = 266 \left( \frac{404}{101} \right)^{\frac{1.4-1}{1.4}} = 395.4K \]
\[ \eta_C = \frac{T_2-T_1}{T'_2-T'_1} \quad \text{or} \quad T'_2 - T'_1 = \frac{395.4 - 266}{0.88} \]

\[ T'_2 = 418.2k \]

\[ P_4 - P_1 = 0.03P_1 \quad \therefore \quad P_4 = 1.03P_1 = 1.03 \times 101 = 104kPa \]

\[ P_2 - P_3 = 0.03P_2 \quad \therefore \quad P_3 = 0.97P_2 = 0.97 \times 404 = 392kPa \]

Process 3-4 is isentropic, \[ \therefore T_4 = T_3 \left( \frac{P_4}{P_3} \right)^{\frac{\gamma-1}{\gamma}} \]

\[ = 300 \left( \frac{104}{392} \right)^{\frac{1.4-1}{1.4}} = 202.3K \]

\[ \eta_E = \frac{T_3 - T'_4}{T'_3 - T'_4} \quad \therefore \quad T'_4 = T_3 - \eta_E(T_3 - T_4) \]

\[ T'_4 = 300 - 0.85 \times [300 - 205.3] = 216.53k \]

Refrigeration effect/kg of air \[ = C_p(T_3 - T_4) \]

\[ = 1.005 \times [266 - 216.53] = 50.47kJ/kg \]

Compressor work/kg of air \[ = C_p(T'_2 - T_1) \]

\[ = 1.005 \times [418.2 - 266] = 152.96kJ/kg \]

Turbine work/kg of air \[ W_T = C_p(T_3 - T'_4) \]

\[ = 1.005 \times [300 - 216.53] = 84.9kJ/kg \]

Net work Input/kg of air \[ W_{net} = W_C - W_T \]

\[ = 152.96 - 80.9 = 72.06kJ/kg \]

\[ C.O.P = \frac{RE}{Work} = \frac{46.73}{72.06} = 0.73 \]

Power required per tons of refrigeration \[ = \frac{\text{Refrigeration capacity}}{\text{C.O.P}} \]

Refrigeration capacity = 1 ton = 3.5kJ/s

Mass of air \[ = \frac{\text{Refrigeration capacity}}{\text{RE}} \]

\[ = \frac{3.5}{50.47} = 0.075kg/s \]

Power \[ = W_{net} \times \text{mass of air} / \text{sec} = 72.06 \times 0.075 = 5.42kW \]
Vapour compression refrigeration system

**Introduction**
In vapour compression system, the refrigerants used are ammonia, carbon dioxide, freons etc. the refrigerants alternately undergoes condensation and evaporation during the cycle. When refrigerant enters the evaporator it will be in liquid state and by absorbing latent heat it become vapours. Thus the C.O.P of this system is always much higher that air refrigeration systems.

Schematic Diagram

**Analysis of the cycle**

The various processes are

**Process ab**. The vapour refrigerant entering the compressor is compressed to high pressure and temperature in a isentropic manner.

**Process bc**. This high pressure and high temperature vapour then enters a condenser where the temperature of the vapour first drops to saturation temperature and subsequently the vapour refrigerants condenses to liquid state.

- Process cd. This liquid refrigerant is collected in the liquid storage tank and later on it is expanded to low pressure and temperature by passing it through the throttle valve. At point d we have low temperature liquid refrigerant with small amount of vapour.
- Process da. This low temperature liquid then enters the evaporator where it absorbs heat from the space to be cooled namely the refrigerator and become vapour.

Refrigeration effect = $H_a - H_d$

But process c-d is a throttling process

$H_c = H_d$, \[ R.E = H_a - H_c \]

work done = $H_b - H_a$

\[ C.O.P = \frac{R.E}{work} = \frac{H_a - H_c}{H_b - H_a} \]
- Effect of under cooling the liquid

- Effect of super heating the vapour

Advantages of Vapour compression refrigeration system over air refrigeration system
- Since the working cycle approaches closer to carnot cycle, the C.O.P is quite high.
- Operational cost of vapour compression system is just above 1/4th of air refrigeration system.
- Since the heat removed consists of the latent heat of vapour, the amount of liquid circulated is less and as a result the size of the evaporator is smaller.
- Any desired temperature of the evaporator can be achieved just by adjusting the throttle valve.

Disadvantages of Vapour compression refrigeration system over air refrigeration system
- Initial investment is high
- Prevention of leakage of refrigerant is a major problem

Refrigerant
A refrigerant is a fluid in a refrigerating system that by its evaporating takes the heat of the cooling coils and gives up heat by condensing the condenser.
Identifying refrigerants by numbers

The present practice in the refrigeration industry is to identify refrigerants by numbers. The identification system of numbering has been standardized by the American society of heating, refrigerating and air conditioning engineers (ASHRAE), some refrigerants in common use are

<table>
<thead>
<tr>
<th>Refrigeration</th>
<th>Name and Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-11</td>
<td>Trichloromonofluoromethane CCl₃F</td>
</tr>
<tr>
<td>R-12</td>
<td>Dichlorodifluoromethane CCl₂F₂</td>
</tr>
<tr>
<td>R-22</td>
<td>Monochlorodifluoromethane CHClF₂</td>
</tr>
<tr>
<td>R-717</td>
<td>Ammonia NH₃</td>
</tr>
<tr>
<td>R114(R40)</td>
<td>Azeotropic mixture of 73.8% (R-22) and 26.2%</td>
</tr>
<tr>
<td>R-500</td>
<td>R-152a</td>
</tr>
<tr>
<td>R502</td>
<td>Azeotropic mixture of 48.8% (R-22) and 51.2%</td>
</tr>
<tr>
<td>R-764</td>
<td>Sulphur Dioxide SO₂</td>
</tr>
</tbody>
</table>

Properties of Refrigerants

- **Toxicity:**
  It obviously desirable that the refrigerant have little effect on people

- **Inflammability:**
  Although refrigerants are entirely sealed from the atmosphere, leaks are bound to develop. If the refrigerant is inflammable and the system is located where ignition of the refrigerant may occur, a great hazard is involved.

- **Boiling Point.**
  An ideal refrigerant must have low boiling temperature at atmospheric pressure

- **Freezing Point**
  An ideal refrigerant must have a very low freezing point because the refrigerant should not freeze at low evaporator temperatures.

- **Evaporator and condenser pressure.**
  In order to avoid the leakage of the atmosphere air and also to enable the detection of the leakage of the refrigerant, both the Evaporator and condenser pressure should be slightly above the atmosphere pressure.

- **Chemical Stability**
  An ideal refrigerant must not decompose under operating conditions.
• **Latent heat of Evaporation.**
  The Latent heat of Evaporation must be very high so that a minimum amount of refrigerant will accomplish the desired result; in other words, it increases the refrigeration effect.
• **Specific Volume**
  The Specific Volume of the refrigerant must be low. The lower specific volume of the refrigerant at the compressor reduces the size of the compressor.

• **Specific heat of liquid vapour.**
  A good refrigerant must have low specific heat when it is in liquid state and high specific heat when it is vaporized.

• **Viscosity**
  The viscosity of the refrigerant in both the liquid and vapour state must be very low as improved the heat transfer and reduces the pumping pressure.

• **Corrosiveness.**
  A good refrigerant should be non-corrosive to prevent the corrosion of the metallic parts of the refrigerator.

• **Coefficient of performance**
  The coefficient of performance of a refrigerant must be high so that the energy spent in refrigeration will be less.

• **Odour.**
  A good refrigerant must be odourless, otherwise some foodstuff such as meat, butter, etc. loses their taste.

• **Lekage**
  A good refrigerant must be such that any leakage can be detected by simple test.

• **Oil solvent properties.**
  A good refrigerant must be not react with the lubricating oil used in the refrigerator for lubricating the parts of the compressor.

• **Cost**
  The cost of the refrigerant is the major important, it will easily available and low cost.
Problem 1: 20 tons of ice is produced from water at 20°C to ice at -6°C in a day of 24 hours, when the temperature range in the compressor is from -15°C to 25°C. The condition of the vapour is dry at the end of compression. Assuming relative C.O.P as 80%, calculate the power required to drive the compressor. Take $C_p$ = 2.1 kJ/kg, Latent heat of ice = 335 kJ/kg

<table>
<thead>
<tr>
<th>Temp $^\circ$C</th>
<th>Liquid</th>
<th>Vapour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Enthalpy $hf$</td>
<td>Entropy $Sf$</td>
</tr>
<tr>
<td>25</td>
<td>100.04</td>
<td>0.347</td>
</tr>
<tr>
<td>-15</td>
<td>-54.55</td>
<td>-2.1338</td>
</tr>
</tbody>
</table>

To find the condition of vapour at point 'a'.

Entropy at a = Entropy at b

$$s_{fa} + x_a s_{ga} = s_{gb}$$

$$-2.1338 + x_a 5.0585 = -2.1338 = 4.4852$$

$$x_a = 0.92$$

$$H_a = h_{fa} + x_a h_{ga} = 54.55 + 0.92[1304.99 - (-54.55)]$$

$$H_a = 1196.22 \text{kJ/kg}$$

$$H_c = h_{fc} = 100.04 \text{kJ/kg}$$

$$H_b = h_{gb} = 1319.2 \text{kJ/kg}$$

Refrigeration effect $R.E = H_a - H_c$

$$= 1196.22 - 100.04 = 1096.18 \text{kJ/kg}$$

work $= H_b - H_a$

$$= 1319.2 - 1196.22 = 122.98 \text{kJ/kg}$$
Problem 2: A vapour compression refrigerator working with Freon-12 has its temperature range -10ºC and 30ºC. The Vapour enters the compressor dry and under cooled by 5ºC in the condenser. For a capacity of 15 TOR, find: (a) C.O.P (b) mass of Freon (c) Power required.

Cp for vapour = 0.56kJ/kgK
Cp for liquid = 1.003kJ/kgK

Solution:
Refrigeration capacity = 15 TOR

From tables the properties of Freon 12 are

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Enthalpy</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hf</td>
<td>Hfg</td>
</tr>
<tr>
<td>30</td>
<td>64.59</td>
<td>135.03</td>
</tr>
<tr>
<td>-10</td>
<td>26.87</td>
<td>156.31</td>
</tr>
</tbody>
</table>

\[ C.O.P = \frac{RE}{work} = \frac{1096.18}{122.98} = 8.913 \]
Relative C.O.P = 0.8
Actual C.O.P = 0.8 \times 8.913 = 7.13
Heat extracted/kg of ice = C_{pw} (20 - 0) + Latent heat + C_{pice} [0 - (-6)]
= 4.187 \times 20 + 335 + 2.1 \times 6 = 431.34

Mass of ice produced/sec = \frac{20 \times 1000}{24 \times 3600} = 0.231kg/s
Actual heat extracted/sec = 431.34 \times 0.231
= 99.84kJ/s
Actual C.O.P = \frac{Actual heat extracted/sec}{Actual work/sec}
∴ Actual work/sec = \frac{99.84}{7.13} = \frac{99.84}{7.13}

Power = 14kW
To find the condition of vapour at point 'b'.

Entropy at b = Entropy at a

\[ s_{gb'} + C_{pv} \frac{T_{b'}}{T_{b'}} = s_{ga} \]

\[ 0.6853 + 0.56 \ln \frac{T_{b'}}{303} = 0.7019 \]

\[ T_{b'} = 312.15 \text{ K} \]

\[ H_b = h'_{gb'} + C_{pv}(T_b - T_{b'}) \]
\[ = 100.62 + 0.56(312.15 - 303) = 204.74 \text{ kJ/kg} \]

\[ H_a = h_{ga'} = 183.19 \text{ kJ/kg} \]

\[ H_c = h_{gc'} - C_{PL}(T_c - T_c) \]
\[ = 64.59 - 1.003(30 - 25) = 59.575 \text{ kJ/kg} \]

\[ R.E = H_a - H_c = 183.19 - 59.575 = 123.61 \text{ kJ/kg} \]

\[ \text{work} = H_b - H_a = 204.74 - 183.19 = 21.55 \text{ kJ/kg} \]

\[ C.O.P = \frac{R.E}{\text{work}} = \frac{123.61}{21.55} = 5.73 \]

Refrigeration capacity = 15tons
\[ = 15 \times 3.5 = 52.5 \text{ kJ/kg} \]

Mass of freon = \[ \frac{\text{Refrigerant capacity}}{\text{R.E}} \]
\[ = \frac{52.5}{123.61} = 0.424 \text{ kJ/s} \]

Power required = work/kg x Mass of freon/s
\[ = 21.55 \times 0.424 = 9.152 \text{ kW} \]

**Problem3**: A food storage locker requires a refrigeration system of 12 tons capacity at an evaporator temperature of -8°C and a condenser temperature of 30°C. The refrigerant freon-12 is sub cooled to 25°C before entering the expansion valve and the vapour is superheated to -2°C before entering the compressor. The compression of the refrigerant is reversible adiabatic. A double action compressor with stroke equal to 1.5 times the bore is to be used operating at 900 rpm.

Determine
- COP
- Theoretical piston displacement/min
- Mass of refrigerant to be circulated/min
- Theoretical bore and stroke of the compressor.
Take liquid specific heat of refrigerant as 1.23 kJ/kg K and the specific heat of vapour refrigerant is 0.732 kJ/kg K.

Solution:
From tables the properties of Freon 12 are

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Enthalpy</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hf</td>
<td>hg</td>
</tr>
<tr>
<td>30</td>
<td>64.59</td>
<td>199.62</td>
</tr>
<tr>
<td>-8</td>
<td>25.75</td>
<td>184.2</td>
</tr>
</tbody>
</table>

\[ C_{pv} = 0.732kJ / kgK \]
\[ C_{pl} = 1.235kJ / kgK \]

Entropy at b = entropy at a

\[ S_{gb} + C_{pv} Ln \frac{T_b}{T_{b'}} = S_{ga} + C_{pv} Ln \frac{T_a}{T_{a'}} \]

\[ 0.6853 + 0.732 \times \frac{T_b}{303} = 0.7002 + 0.733 \times \frac{271}{265} \]

\[ T_b = 317.22K \]

\[ H_a = h_{ga} + C_{pv}(T_a - T_a') \]
\[ = 184.2 + 0.732(271 - 265) \]
\[ = 188.59kJ/kg \]

\[ H_b = h_{gb} - C_{pv}(T_b - T_b') \]
\[ = 199.62 + 0.732(318.22 - 303) \]
\[ = 210.02kJ/kg \]

\[ H_c = h_{gc} - C_{pl}(T_c - T_c) \]
\[ = 64.59 - 1.235(303 - 298) = 58.41kJ/kg \]

R.E = \[ H_a - H_c = 188.59 - 58.41 = 130.18kJ / kg \]

work = \[ H_b - H_a = 210.02 - 188.59 = 21.43kJ / kg \]

\[ C.O.P = \frac{R.E}{work} = \frac{130.18}{21.43} = 6.07 \]
Mass of refrigerant = \( \frac{Re f . capacity}{RE} \)
\[
= \frac{12 \times 3.5}{130.18} = 0.322 \text{ kg/s}
\]
\[
= 0.322 \times 60 = 19.35 \text{ kg/min}
\]
From tables at \(-8^\circ\text{C}, V_{g\alpha} = 0.0441995 \text{ m}^3/\text{kg}\)
\[
\frac{PV_{g\alpha}}{T_{\alpha'}} = \frac{PV_{\alpha}}{T_{\alpha}}
\]
\[
V_{\alpha} = \frac{T_{\alpha}xV_{g\alpha'}}{T_{\alpha'}} = \frac{271}{265} \times 0.0441995 = 0.0452
\]

*Theoretical* piston displacement \(V = \text{mass } xV_{\alpha}\)
\[
= 19.35 \times 0.0452 = 0.87462 \text{ m}^3/\text{min}
\]

\[V = \frac{2\pi}{4} d^2 LN \quad (L = 1.5d)\]

\[
0.87462 = \frac{2\pi d^2 x 1.5d}{4} x 900
\]
\[
= 0.0203 \text{ m}
\]

\[d = 0.0738 \text{ m} \]
\[= 7.38 \text{ cm}\]

\[L = 1.5d = 1.5 \times 7.38 \]
\[= 11.08 \text{ cm}\]
Problem 4:
A vapour compression refrigeration system of 5kW cooling capacity operates between -10ºC and 30ºC. The enthalpy of refrigerant vapour after compression is 370kJ/kg. Find the COP, refrigerating effect, mass flow rate of the refrigerant and the compressor power. The extract of the refrigerant property table is given below.

<table>
<thead>
<tr>
<th>Temp</th>
<th>Pressure</th>
<th>Vf</th>
<th>Vg</th>
<th>hf</th>
<th>hg</th>
<th>Sf</th>
<th>Sg</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>bar</td>
<td>m³/kg</td>
<td></td>
<td>kJ/kg</td>
<td>kJ/kg</td>
<td>kJ/kgK</td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td>226</td>
<td>0.7x10⁻³</td>
<td>0.08</td>
<td>190</td>
<td>345</td>
<td>0.95</td>
<td>1.5</td>
</tr>
<tr>
<td>30</td>
<td>7.5</td>
<td>0.77x10⁻³</td>
<td>0.02</td>
<td>220</td>
<td>220</td>
<td>1.10</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Solution:
Assume the condition before compression as dry saturated vapour.

\[ H_c = h_{fc} = 220 \text{kJ/kg} \]
\[ H_a = h_{ga'} = 345 \text{kJ/kg} \]
\[ H_b = 370 \text{kJ/kg (given)} \]
\[ \text{R.E.} = H_a - H_c = 345 - 220 = 125 \text{kJ/kg} \]
\[ \text{work} = H_b - H_a = 370 - 345 = 25 \text{kJ/kg} \]

\[ C.O.P = \frac{\text{R.E.}}{\text{work}} = \frac{125}{25} = 5 \]

Refrigeration capacity = 5kW or kJ/s

Mass of refrigerant = \[ \frac{\text{R.E.,capacity}}{\text{R.E.}} \]
\[ = \frac{5}{125} = 0.04 \text{kg/s} \]

Compressor work = \text{work.kg} \times \text{mass of refrigerant}
\[ = 25 \times 0.04 = 1 \text{kW} \]
**Problem 5:** A vapour compression refrigerator uses methyl chloride and works in the pressure range of 1.19 bar and 5.67 bar. At the beginning of compression, the refrigerant is 0.96 dry and at the end of isentropic compression, its temperature is 55°C. The refrigerant liquid leaving the condenser is saturated. If the mass flow of refrigerant is 1.8 kg/min, determine COP

The rise in temperature of cooling water if the water flow rate is 16 kg/min. The properties of methyl chloride is given below

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Pressure (bar)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>hf</td>
<td>Hfg</td>
</tr>
<tr>
<td>30</td>
<td>1.19</td>
<td>64.59</td>
<td>135.03</td>
</tr>
<tr>
<td>-10</td>
<td>5.67</td>
<td>26.87</td>
<td>156.31</td>
</tr>
</tbody>
</table>

*Take* specific heat of super heat methyl chloride as 0.75 kJ/kg K

*Solution*

\[ x_a = 0.96 \]

\[ T_b = 55°C \]

\[ H_a = h_{fa} + x_a(h_{fga}) = h_{fa} + x_a(h_{ga} - h_{fa}) \]

\[ = 430.1 + 0.96(455.2 - 30.1) = 438.196 \text{ kJ/kg} \]

\[ H_b = h_{gb} - C_p(T_b - T_{fb}) \]

\[ = 476.5 + 0.75(55 - 25) = 499 \text{ kJ/kg} \]

\[ H_c = h_{fc} = 100.5 \text{ kJ/kg} \]

\[ R.E = H_a - H_c = 438.196 - 100.5 = 337.669 \text{ kJ/kg} \]

\[ work = H_b - H_a = 499 - 438.196 = 60.8 \text{ kJ/kg} \]

\[ \text{C.O.P} = \frac{R.E}{work} = \frac{337.669}{60.8} = 5.55 \]

*Heat* lost by the vapour in the condenser

\[ = \text{heat gain by cooling water} \]
Vapour absorption refrigeration system

General
The absorption refrigeration system is a heat-operated unit which used a refrigerant that is alternately absorbed and liberated by the absorbent.

Simple Absorption system
The minimum number of primary units essential in an absorption system include an evaporation, absorber, generator and condenser.

![Diagram of absorption refrigeration system]

An expansion valve, pressure reducing valve, and a pump are used in a conventional two-fluid cycle, but the pump can be eliminated by adding a gaseous third fluid. A simple absorption cycle is shown in figure

This cycle differs from a vapour compression cycle by the substitution of an absorber, generator, pumps and reducing valve for the compressor. Various combinations of fluids may be used, but that of ammonia, a strong solution that contains about as much ammonia as possible; a weak solution contains considerably less ammonia.

The weak solution containing very little ammonia is sprayed or otherwise exposed in the absorber and absorbs ammonia coming from the evaporation. Absorption of the ammonia lowers the pressure in the absorber, which in turn draws more ammonia vapour from the evaporator. Usually some form of cooling is employed in the absorber to remove the heat of condensation and the heat of solution evolve there.

The strong solution is then pumped into a generator, which is at higher pressure and is where heat is applied the heat vapourises the ammonia driving it out of solution and into the condenser, where it liquefied. The liquid ammonia passes on to the receiver if a separate one is used, or through the expansion valve and into the evaporator. The weak solution left in the generator after the ammonia has been drive off flows through the reducing valve back to the absorber.

\[
m_r C_p (T_b - T_v) + m_r h_{fgb} = m_w C_p \times \text{temperature rise} \\
1.8 \times 0.75(55 - 25) + 1.8(476.5 - 100.5) \\
= 16 \times 4.187 \times \text{temperature rise} \\
\therefore \text{Temperature rise} = 10.7^\circ C
\]