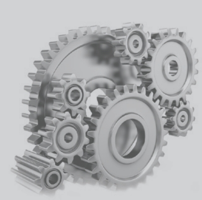
# MECHANICAL ENGINEERING

# Refrigeration & Air-Conditioning



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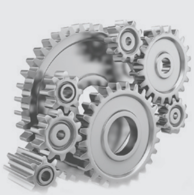



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CHAPTER

# 2

# Vapour Compression Refrigeration System

## 2.1 INTRODUCTION

Vapour Compression Refrigeration Systems (VCRS) are the most commonly used among all refrigeration systems. These systems belong to the general class of vapour cycles, wherein the working fluid (refrigerant) undergoes phase change at least during one process. In a vapour compression refrigeration system, refrigeration is obtained as the refrigerant evaporates at low temperature. The input to the system is in the form of mechanical energy required to run the compressor. Hence, these systems are also called as mechanical refrigeration systems.

VCRS are available to suit almost all applications with the refrigeration capacities ranging from few Watts to few mega Watts. A wide variety of refrigerants used in these systems to suit different applications, capacities, etc.

The following points should be carefully understood before studying the vapour compression cycle :

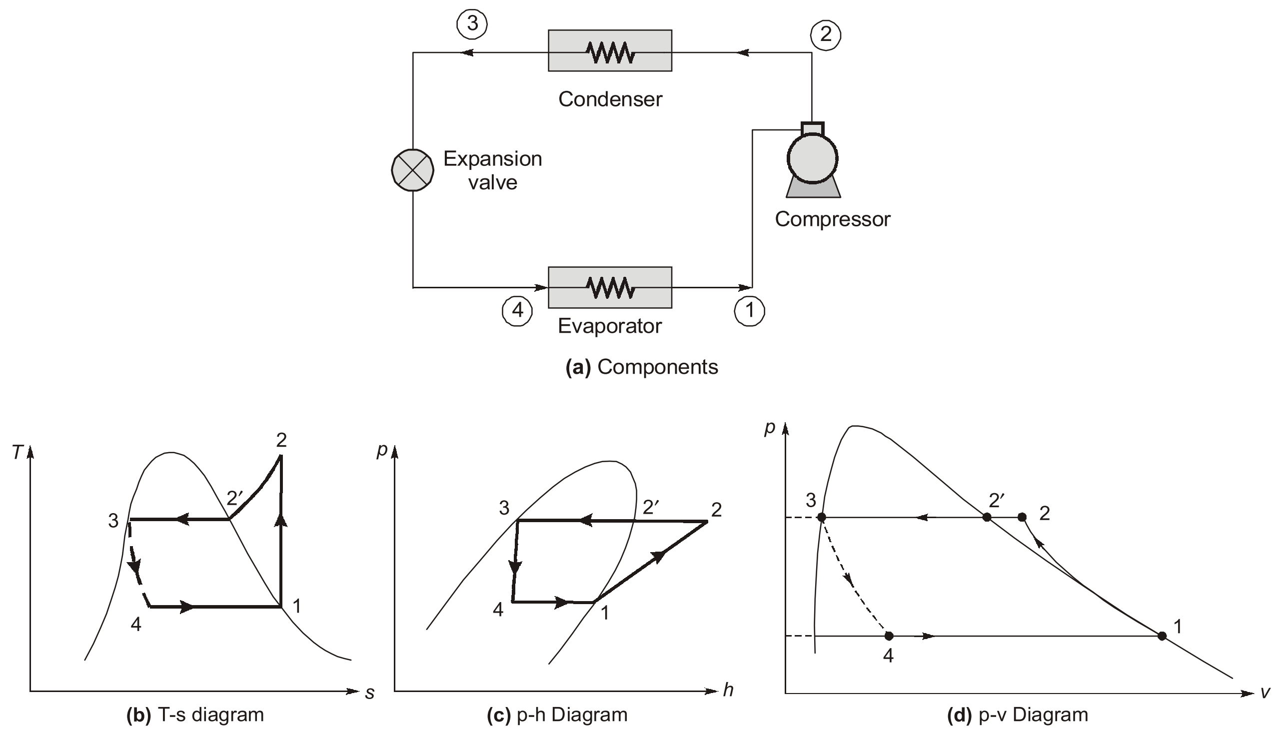
1. Fluids absorb heat while changing phase from liquid to vapour and release it while changing phase from vapour to liquid.
2. The temperature remains constant during the phase change, provided the pressure remains constant.
3. Heat flows naturally only from a body at a higher temperature to a body at lower temperature.
4. The evaporating and condensing units are made from metals having high thermal conductivity for better heat transfer.
5. Heat energy and other forms of energy are interchangeable. For example, electric energy may be converted to heat energy; heat energy to electrical energy and further to mechanical energy.

## 2.2 SIMPLE VAPOUR COMPRESSION REFRIGERATION SYSTEM

Vapour compression refrigeration system can be considered as a modification to the Reversed Carnot cycle. Figure (a) shows the basic components of a simple vapour compression refrigeration system. Instead of isothermal heat addition and rejection, both the heat addition and the rejection are carried out at constant pressure. But since the heat addition and rejection processes are occurring during phase change, they automatically become processes with constant temperature. The expansion of the refrigerant is done by throttling process (isenthalpic) instead of isentropic process.

The figure (b), (c), (d) represents the T-s, p-h and p-v diagram of a simple-saturated single stage VCRS cycle **(Standard VCRS)**.

The term saturated indicates that the state of the refrigerant at the exit of condenser and the evaporator is saturated as evident from figure below.




(a) Components
(b) T-s diagram
(c) p-h Diagram
(d) p-v Diagram

**Figure:** Simple saturated vapour compression refrigeration system

Following processes are carried out in different components of a simple VCRS cycle:

- **Process 1-2:** Reversible adiabatic (isentropic) compression in compressor
- **Process 2-3:** Constant pressure heat rejection in condenser
- **Process 3-4:** Isenthalpic expansion in expansion valve
- **Process 4-1:** Constant pressure heat addition in evaporator

## 2.2.1 Analysis of standard vapour compression refrigeration system

- **Process 1-2:**

  Isentropic compression, $s_2 = s_1,\ Q = 0$

  Compressor work done per unit mass,

  $$W = -\int v\,dp = -\int dh = -(h_2 - h_1)$$

  Work input per unit mass $= h_2 - h_1$

  Power input to the compressor, $\dot{W} = \dot{m}(h_2 - h_1)$

  where, $\dot{m}$ is the mass flow rate of refrigerant.

- **Process 2-3:**

  Heat rejected in the condenser per unit mass,

  $$q_{2\text{-}3} = h_2 - h_3$$

  $$Q_H = \dot{m}(h_2 - h_3)$$

- **Process 3-4:**

  Isenthalpic expansion, $h_3 = h_4 = h_{f4} + x_4(h_1 - h_{f4})$

- **Process 4-1:**

  Heat addition per unit mass (Refrigeration effect),

## OBJECTIVE BRAIN TEASERS

**Q.1** In vapour compression refrigeration system, with simple saturated cycle, the isentropic work of expansion is replaced with throttling process because

(a) Positive work of expander is very small to justify cost of expander
(b) Throttling device gives better COP
(c) Throttling device is easy to operate
(d) Throttling device increases refrigeration capacity

**Q.2** Work of compression of the fluid in vapour absorption system of refrigeration as compared to that in vapour compression refrigeration system is

(a) More (b) Less
(c) May be more or less (d) Unpredictable

**Q.3** Use of liquid suction heat exchanger or liquid vapour regenerative heat exchanger in vapour compression system is justified because

(a) COP of cycle improves irrespective of any refrigerant used
(b) Horse power per ton decreases irrespective of any refrigerant used
(c) Suction volume per ton decreases irrespective of any refrigerant used
(d) Super heating in liquid suction exchanger is preferable to super heating in evaporator itself

**Q.4** Which of the following statements pertaining to a vapour compression type refrigerator are correct?

(a) The condenser rejects heat to the surroundings from the refrigerant.
(b) The evaporator absorbs heat from the surroundings to be cooled.
(c) Both the condenser and the evaporator are heat exchangers with refrigerants as the common medium.
(d) The amount of heat exchanged in condenser and evaporator are equal under steady conditions.

[MSQ]

**Q.5** In system *A* vapours are superheated by 10°C in the evaporator, while in system *B* vapours are superheated by 10°C in liquid vapour regenerative heat exchanger. Other conditions of the systems are same. Then

(a) COP of *A* = COP of *B*
(b) COP of both *A* and *B* > COP of reverse Carnot cycle
(c) COP of *A* > COP of *B*
(d) COP of *A* < COP of *B*

**Q.6** **Statement (I):** Power input per TR of a refrigeration system increases with decrease in evaporator temperature.

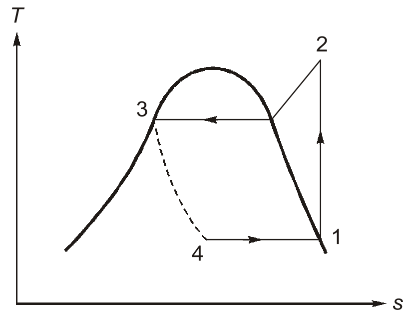
**Statement (II):** COP of a refrigeration system decreases with decrease in evaporator temperature.

(a) Both Statement (I) and Statement (II) are true and Statement (II) is the correct explanation of Statement (I).
(b) Both Statement (I) and Statement (II) are true but Statement (II) is not a correct explanation of Statement (I).
(c) Statement (I) is true but Statement (II) is false.
(d) Statement (I) is false but Statement (II) is true.

**Q.7** Which one of the following sequence is correct in vapour compression cycle?

(a) Iso-enthalpic expansion, iso-baric heat rejection, isentropic compression, iso-baric heat absorption
(b) Isentropic compression, iso-baric heat rejection, iso-enthalpic expansion, iso-baric heat absorption
(c) iso-baric heat absorption, isentropic compress, iso-baric heat rejection, iso-enthalpic expansion
(d) iso-enthalpic expansion, iso-baric heat absorption isentropic compression, iso-baric heat rejection

13. (c)




Ideal COP,

$$(COP)_{ideal} = \frac{h_1 - h_4}{h_2 - h_1}$$

$\because$ $h_1 = 450$ kJ/kg, $h_2 = 525$ kJ/kg,

$$h_4 = h_3 = 225 \text{ kJ/kg}$$

$$\therefore \quad (COP)_{ideal} = \frac{450 - 225}{525 - 450} = 3$$

$$\therefore \quad (COP)_{act} = 0.6 \times 3 = 1.8$$

or $$\frac{W_{in}}{Q_{in}} = \frac{1}{1.8} = 0.55 \text{ kW per kW cooling}$$

14. (b)

In a thermoelectric refrigerator, the cooling capacity is equal to the electric power supplied or even less than that because of some losses. While in VCRS, generally the COP is more than one.

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## CONVENTIONAL BRAIN TEASERS

Q.1 A commercial refrigerator with refrigerant R-134*a* as a working fluid is used to keep the refrigerated space at –30°C by rejecting its waste heat to cooling water that enters the condenser at 18°C at a rate of 0.25 kg/s and leaves at 26°C. The refrigerant enters the condenser at 1.2 MPa and 65°C and leave at 42°C. The inlet state of the compressor is 60 kPa and –34°C and the compressor is estimated to gain a net heat of 450 W from the surroundings.

Determine:

(i) The quality of the refrigerant at the evaporator inlet.

(ii) The refrigeration load.

(iii) The COP of the refrigerator.

(iv) The theoretical maximum refrigeration load for the same power input to compressor.

Take specific heats for water as 4.18 kJ/kgK and for liquid refrigerant as 1.0415 kJ/kgK. The properties of R-134a:

| $p$ bar | $T_{sat}$ °C | Specific enthalpy | | Specific entropy | |
|---|---|---|---|---|---|
| | | $h_f$ kJ/kg | $h_g$ kJ/kg | $s_f$ kJ/kgK | $s_g$ kJ/kgK |
| 0.6 | – 37.07 | 3.46 | 224.72 | 0.0147 | 0.9520 |
| 12 | 46.32 | 115.76 | 270.99 | 0.4164 | 0.9023 |

| $p$ = 0.6 bar ($T_{sat}$ = – 37.07°C) | | $p$ = 12 bar ($T_{sat}$ = 46.32°C) | |
|---|---|---|---|
| $T$ °C | $h$ kJ/kg | $T$ °C | $h$ kJ/kg |
| Sat | 224.72 | 60 | 287.44 |
| – 20 | 237.98 | 70 | 298.96 |

CHAPTER

4

# Air Refrigeration Systems

## 4.1 INTRODUCTION

Air cycle refrigeration systems belong to the general class of gas cycle refrigeration systems, in which a gas is used as the working fluid. Air is used as a refrigerant (working medium) in air refrigeration systems. Air absorbs heat from the low temperature space and rejects heat to the high temperature surroundings while undergoing an air refrigeration cycle. Air does not change its phase while undergoing a cyclic process, consequently, all internal heat transfer processes are sensible heat transfer processes. Therefore, the heat carrying capacity per unit mass of air is very small in comparison to that of a refrigerant of a vapour compression refrigeration cycle. To obtain a required refrigeration effect, a large quantity of air needs to be handled, requiring a bigger-sized compressor, heat exchanger and expansion device. Gas cycle refrigeration systems have applications in aircraft cabin cooling and in the liquefaction of various gases.

In the high-speed passenger aircraft, jet aircraft and missiles has introduced the need for compact and simple refrigeration systems, capable of high capacity. The cooling requirement of an ordinary passenger aircraft is around 8TR.

## 4.2 BELL-COLEMAN OR REVERSED BRAYTON OR JOULE CYCLE

The Bell-Coleman refrigerator using air as a refrigerant is shown with the help of a block diagram in figure. It consists of a compressor, a cooler, an expander and a refrigerator. The Bell-Coleman air refrigeration cycle is the modification of the reversed Carnot cycle with air as a working medium. It can be operated as an open cycle shown in figure, in which the cold air available at the outlet of the expander is used for refrigeration and is let out in the atmosphere. In the closed cycle the same air is circulated repeatedly. The cold air available at the outlet of the expander is employed to cool the other fluid in the heat exchanger. The other fluid acts as the secondary refrigerant in this cycle.

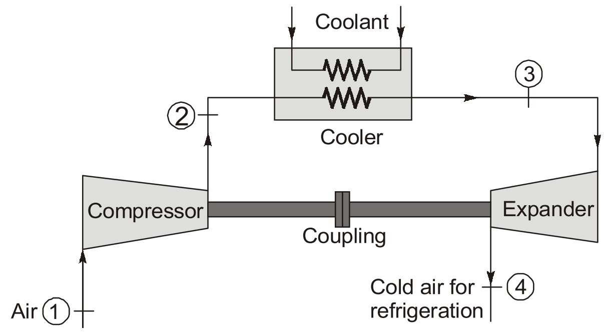



**Figure:** Bell-Coleman air refrigeration open cycle

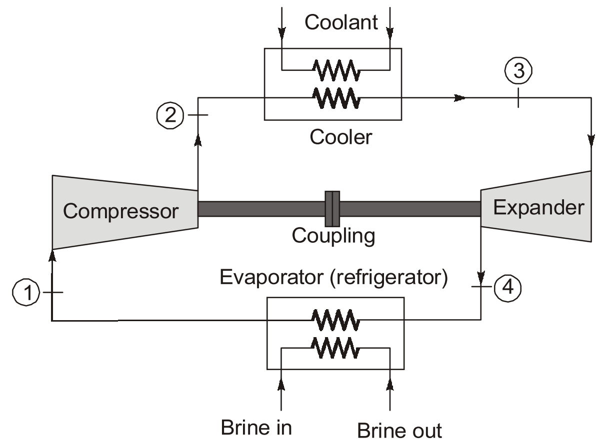



**Figure:** Bell-Coleman air refrigeration closed cycle (dense air cycle)

The cycle is represented on p-v and T-s diagrams as shown in figure (a) and figure (b) respectively

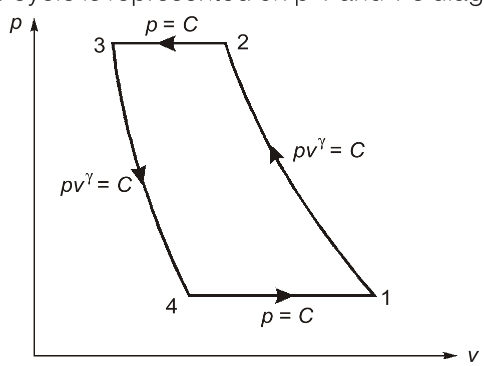



**Figure (a):** Bell-Coleman air cycle on p-v diagram

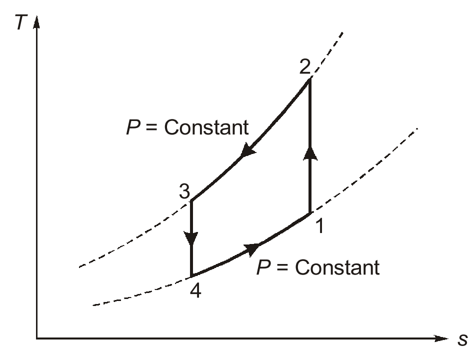



**Figure (b):** Bell-Coleman cycle on T-s diagram

The four processes of the closed cycle are as follows:

- **Isentropic compression process (1-2):** The air from the refrigerator is drawn into the compressor and compressed isentropically to state 2. During compression, both pressure and temperature increase while the specific volume decreases from $v_1$ to $v_2$. During the isentropic process, no heat is absorbed or rejected by the air.
- **Constant pressure heat rejection process (2-3):** The high temperature air is cooled from temperature $T_2$ to $T_3$ in the cooler at constant pressure. Here the frictional pressure loss on account of the friction between the air and the heat exchanger is neglected. The specific volume decreases from $v_2$ to $v_3$. Applying steady flow energy equation and second T-ds equation, the heat rejected per kg of air during the process is:

$$Q_{2\text{-}3} = h_2 - h_3 = c_p(T_2 - T_3)$$

- **Isentropic expansion process (3-4):** The air is expanded isentropically from pressure $p_2$ ($p_3 = p_2$) to $p_4$ ($p_4 = p_1$ = atmospheric pressure), while the temperature of air also decreases from $T_3$ to $T_4$. The specific volume of air increases from $v_3$ to $v_4$. During this no heat exchange takes place.
- **Constant pressure heat absorption process (4-1):** The cold air from the expander is circulated through the refrigerator where it absorbs heat from brine and thus cools the brine. During this, the temperature of the air increases from $T_4$ to $T_1$ and the specific volume increases from $v_4$ to $v_1$. The heat absorbed from the refrigerator during constant pressure process per kg of air is

and $$\eta_T = \frac{T_4 - T_5'}{T_4 - T_5} \Rightarrow 0.9 = \frac{340 - T_5'}{340 - 217.84}$$

$$T_5' = 230.06 \text{ K}$$

(a) $$\dot{m} = \frac{Q}{RE} = \frac{Q}{c_p(T_6 - T_5')}$$

$$= \frac{105}{1.004 \times (300 - 230.06)} = 1.495 \text{ kg/s}$$

(b) $$\text{COP} = \frac{Q}{W} = \frac{Q}{\dot{m}c_p(T_3' - T_2 - T_4 + T_5')}$$

$$= \frac{105}{1.004 \times (499.54 - 303 - 340 + 230.06) \times 1.495}$$

$$\text{COP} = 0.807$$

(c) $$\text{Specific power} = \frac{\text{Work (KW)}}{\text{Capacity (TR)}} = \frac{129.98}{30} = 4.332 \text{ kW/TR}$$

## OBJECTIVE BRAIN TEASERS

**Q.1** The closed air system as compared to open air system for same range of temperature using Bell-Coleman system gives
(a) Higher power/ton of refrigeration
(b) Lower power/ton of refrigeration
(c) Same power/ton of refrigeration
(d) Unpredictable results

**Q.2** A Bell–Coleman cycle operates on which of the following cycles
(a) Reverse Diesel cycle
(b) Reverse Carnot cycle
(c) Reverse Brayton cycle
(d) Reverse Otto cycle

**Q.3** The expression for COP of reversed Brayton cycle is ($r_p$ is the pressure ratio)

(a) $\dfrac{1}{r_p^{\gamma-1/\gamma} - 1}$ (b) $\dfrac{1}{r_p^{\gamma} - 1}$

(c) $\dfrac{1}{r_p^{\gamma-1/\gamma}}$ (d) $\dfrac{1}{r_p^{\gamma/\gamma-1} + 1}$

**Q.4** Match **List-I** (Cycle) with **List-II** (Equipment) and select the correct answer using the codes given below the lists:

**List-I**
A. Air refrigeration
B. Vapour compression refrigeration
C. Vapour absorption
D. Steam jet refrigeration

**List-II**
1. Absorber
2. Flash chamber
3. Turbine
4. Compressor

**Codes:**

| | A | B | C | D |
|---|---|---|---|---|
| (a) | 3 | 2 | 1 | 4 |
| (b) | 1 | 4 | 3 | 2 |
| (c) | 3 | 4 | 1 | 2 |
| (d) | 1 | 2 | 3 | 4 |

**Q.5** An air refrigeration working on Brayton cycle used for food storage provides 30 TR. The temperature at entry of compressor is 7°C and temperature at exit of cooler is 27°C. Then temperature at exit of compressor is

[Take $C_P = 1$ kJ/kgK, $\dot{m}_{ref} = 3000$ kg/h]

(a) 390.5 K (b) 450.7 K
(c) 545.4 K (d) 650.7 K

## CONVENTIONAL BRAIN TEASERS

**Q.1** An air refrigerator works between the pressure limits of 1 bar and 5 bar. The temperature of air entering the compressor and expansion cylinder are 10°C and 25°C respectively.

The expansion and compression follows the law $PV^{1.3} = C$, find the following:

(i) Theoretical COP of refrigeration cycle.

(ii) If the load on refrigerating machine is 10 tons, then find the amount of air circulated per minute through the system assuming the actual COP is 50% of theoretical COP.

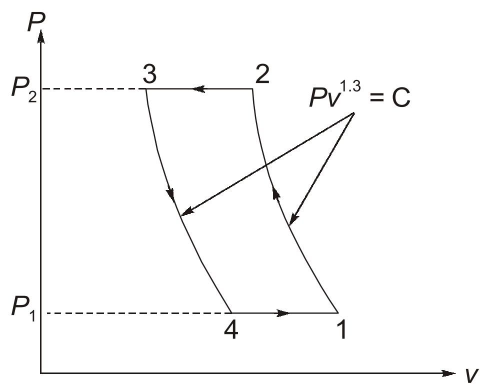
(iii) Length and diameter of a single acting compressor if the compressor runs at 400 rpm and volumetric efficiency is 85%.

[Take for compressor, $\frac{L}{d} = 1.5$, $C_P = 1$ kJ/kg°C, $C_V = 0.7$ kJ/kg°C for air]

**Solution:**

Given: $P_1 = 1$ bar, $P_2 = 5$ bar, $T_1 = 10°C = 283$ K, $T_3 = 25°C = 298$ K

The working cycle is shown below:




(i)

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{1.3-1}{1.3}} = 283 \times 5^{0.23} = 410.28 \text{ K}$$

$$T_4 = \frac{T_3}{\left(\frac{P_2}{P_1}\right)^{\frac{1.3-1}{1.3}}} = \frac{298}{5^{0.23}} = 205.55 \text{ K}$$

Heat absorbed in refrigerator per kg of air $= C_P(T_1 - T_4) = 1 \times (283 - 205.55)$

$= 77.45$ kJ/kg

Work done per kg of air is given by

$$= \frac{n}{n-1} R\left[(T_2 - T_1) - (T_3 - T_4)\right]$$

where, $n = 1.3$, $R = C_P - C_V = 1 - 0.7 = 0.3$ kJ/kg°C