# RRB-JE 2024

## Railway Recruitment Board

Junior Engineer Examination

# Mechanical Engineering

## RAC and Air Compressors

Well Illustrated **Theory** *with*
**Solved Examples** and **Practice Questions**

MADE EASY PUBLICATIONS

# RAC and Air Compressors

## Contents

CHAPTER 01

# Introduction : Refrigerating Machine and Reversed Carnot Cycle

## 1.1 Introduction

- There are essentially two categories of thermal plants
  (i) Thermal power plants/work producing plants.
  (ii) Refrigeration or heat pump plants/work consuming plants.
- Work producing plants or heat engine lead to the conversion of heat to work.
- The objective of work consuming plant is to lead to the flow of heat from a low temperature body to a high temperature body.
- Unit of Refrigerating Capacity is TR (Tonne Refrigeration)
  1 TR = Rate of removal of heat from 1 ton of water to freeze it into ice in 24 hr at 0°C = 50.4 kcal/min
- 1 kcal = 4.18 kJ
  Specific heat of water = 4.18 kJ/kgK
  Specific heat of ice = 2.11 kJ/kgK
  Specific heat of vapour = 1.99 kJ/kgK
  Latent heat of water
  in fusion = 335 kJ/kg (at 0°C)
  in vapourization = 2260 kJ/kg (at 100°C)

**NOTE**

**Production of Low Temperatures**

(i) Throttling expansion of liquid with flashing

(ii) Reversible adiabatic expansion of gas

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

(iii) Irreversible adiabatic expansion of real gas

$$\left(\frac{\partial T}{\partial P}\right)_h = \delta \text{ or } \mu_J$$

This process is known as throttling an $\mu_J$ is called Joule Thomson coefficient.

(iv) Thermoelectric effect or Peltier effect

## 1.2 A Refrigerating machine - The second law interpretation

- A refrigerating machine is a device which will either cool or maintain a body at a temperature below that of the surroudings.
- Schematic Diagram of Refrigerating/AC machine with temperature
- The cooled space is to be maintained at 15°C. The refrigerating machine takes the air at 25°C, and due to evaporation of refrigerant, heat is taken from the air which is cooled to 15°C and returned back to cooled space. During compression, the temperature rises to 65°C while outside temperature is 45°. Hence heat is transferred to outside air while the refrigerant is condensed and temperature of outside air is raised. This condensed/liquid refrigerant is expended by a throttling device and temperature lowers again to 5°C.

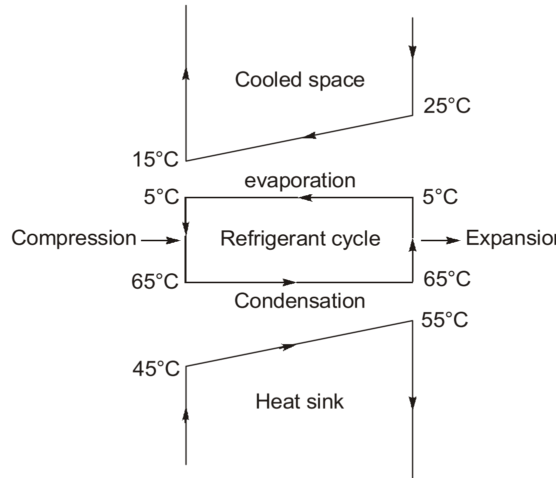


**Figure 1.2**

**Units in Refrigeration**

$$1 \text{ cal} = 4.1868 \text{ Joule (J)}$$
$$1 \text{ horse power} = 746 \text{ Watt (W)}$$
$$1 \text{ unit of power} = 1 \text{ kWH} = 3600 \text{ kJ} = 860 \text{ K cal}$$
$$1 \text{ TR (ton refrigeration)} = 50 \text{ K cal/min} = 3.5167 \text{ kW} = 211 \text{ kJ/min.}$$

**Properties of Air**

$$C_P = 1.005 \text{ kJ/kgK}$$
$$C_V = 0.718 \text{ kJ/kgK}$$
$$R = 0.287 \text{ kJ/kgK}$$
$$\gamma = 1.4$$
$$M = 28.966$$

**Example 1.1** In a 3 ton capacity water cooler, water enters at 30°C and leaves at 15°C steadily, what is the water flow rate per hour?

(a) 60 kg (b) 100 kg
(c) 602 kg (d) 2520 kg

[IES : 2013]

***Solution:*** **(c)**

In steady state, heat absorb from water is equal to the capacity of water cooler.

$$3 \text{ ton} = 3 \times 3.5 \text{ kJ/s} = 3 \times 3.5 \times 3600 \text{ kJ/hr} = 37800 \text{ kJ/hr}$$

Now, $$37800 = \dot{m} C_p \Delta T$$

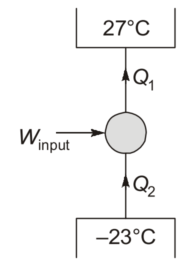
$$\Rightarrow \quad \dot{m} = \frac{37800}{4.18 \times 15} = 602.87 \text{ kg/hr}$$

**Example 1.2** A refrigerator operates between the temperature –23°C and 27°C. If one TR = 3.5 kW, the minimum power required per TR to operate the refrigerator is ________.

(a) 0.5 kW (b) 0.7 kW
(c) 0.9 kW (d) 1 kW

[ESE : 2010]

***Solution:*** **(b)**




$$COP_R = \frac{T_L}{T_H - T_C} = \frac{250}{300-250}$$

For minimum power requirement/TR

$$\frac{1 \times 3.5}{W_{min}} = \frac{250}{300-250}$$

$$\Rightarrow \quad W_{min} = 0.7 \text{ kW}$$

## 1.3 Refrigerating Machine/Heat Pump

- It contains evaporator, compressor, condenser, expander.
- The processes involved in the cycle are as follows:
  - Heat $Q_0$ is absorbed in the evaporator by the evaporation of a liquid refrigerant at a low pressure $P_0$ and corresponding low saturation temperature $T_0$.
  - The evaporated refrigerant vapour is compressed to a high pressure $P_k$ in the compressor consuming work $W$.
  - Heat $Q_k$ is rejected from the condenser to the surrounding.

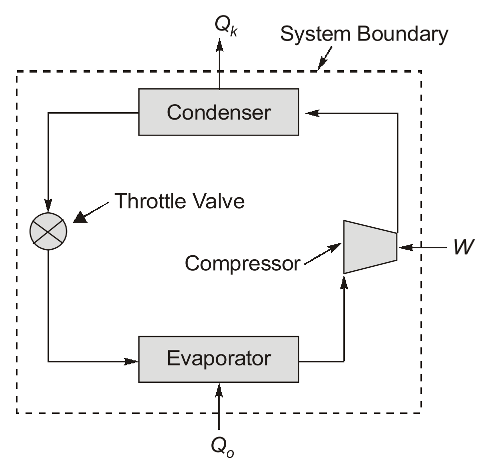



**Figure 1.3**

- When refrigerating machine is used for cooling the space, it is called refrigerator. When the machine is used for heating the space, it is called heat pump.
- Same machine can be used either for cooling or for heating. The main difference between the two is in their operating temperatures.
- A refrigerating machine operates between the ambient temperature and a low temperature. A heat pump operates between the ambient temperature and a high temperature.
- Another essential difference is in their useful functions. In a refrigerating machine the heat exchanger that absorbs heat is connected to the conditioned space. In a heat pump, the heat exchanger that rejects heat is connected to the conditional space.

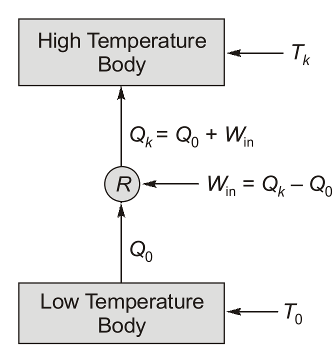



**Figure 1.4**

## 1.4 Coefficient of Performance (COP) or Energy Ratios

$$COP = \text{Energy Ratio} = \frac{\text{useful heat}}{\text{work}}$$

$$(COP)_{ref} = \frac{Q_0}{W} = \frac{Q_0}{Q_k - Q_0}$$

$$(COP)_{pump} = \frac{Q_k}{W} = \frac{Q_k}{Q_k - Q_0} = 1 + \frac{Q_0}{Q_k - Q_0}$$

$$\therefore \quad (COP)_{pump} = 1 + (COP)_{ref}$$

- If refrigerator/heat pump cycle is reversed, it becomes a heat engine.
- Thermal efficiency of heat engine

$$\eta_{th} = \frac{W}{Q_k} = \frac{Q_k - Q_0}{Q_k}$$

$$(COP)_{pump} = \frac{Q_k}{Q_k - Q_0} = \frac{1}{\eta_{th}}$$

$$(COP)_{ref} = \frac{1}{\eta_{th}} - 1 = \frac{1 - \eta_{th}}{\eta_{th}}$$

**NOTE**

- COP of Different Vapour Compression System

| Type of vapour Compression System | COP |
|---|---|
| Water cooled | 3 |
| Air cooled | 2 |
| Domestic Refrigerator | 1 |
| Vapour absorption system | <1 |

- Power consumption of a refrigerator/heat pump

$$1 \text{ H.P.} = \frac{\dot{W} \text{ (in kW)}}{0.746}$$

Refrigerating capacity,

$$(TR) = \frac{Q_0 \text{ (in kW)}}{3.5167}$$

$$\frac{HP}{TR} = \frac{\dot{W}}{0.746} \times \frac{3.5167}{\dot{Q}_0} = 4.71\frac{\dot{W}}{\dot{Q}_0} = \frac{4.71}{(COP)_{Ref}}$$

where, $\dot{W}$ is power consumption (kW) ; $Q_0$ is refrigerating effect (kW).

**Example 1.3** The food compartment of a refrigerator is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, the COP of the refrigerator is :

(a) 2.0 (b) 1/3

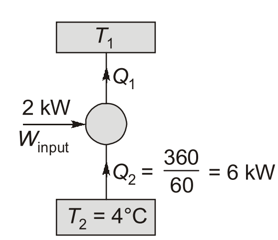
(c) 0.5 (d) 3.0

[SSC-JE : 2014]

***Solution:*** **(d)**

$$COP_R = \frac{Q_2}{W_{input}}$$

$$= \frac{6}{2} = 3$$



### 1.6.1 Draw Back of Using Vapour as Refrigerant in Reversed Carnot Cycle

1. Liquid refrigerant may be trapped in heat of cylinder and damage the compressor valves.
2. Liquid droplets may wash away the lubricating oil from the walls of compressor cylinder.
3. Expander is costly and the work gained in expander is not significant.
   - The Carnot cycle is the most efficient between the given temperature limits ($T_k$ and $T_0$)
   - Second law efficiency or exergetic efficiency for cooling or heating is $(\eta_{II}) = \dfrac{(COP)_{actual}}{(COP)_{Carnot}}$

## 1.7 Gas as Refrigerant in Reversed Carnot Cycle

Refrigerating effect,

$$q_0 = q_{4-1} = RT_0 \ln\frac{v_1}{v_4}$$

Net work = $(W_{2-3})$ − $(W_{4-1})$

$\downarrow$ consumed in compressor; $\downarrow$ gained from expander

[$(W_{1-2})$ and $W_{3-4}$ are same and opposite in sign.
So they cancel each other.]

$$\text{Net work} = RT_k \ln\frac{v_2}{v_3} - RT_0 \ln\frac{v_1}{v_4}$$

$$= R(T_k - T_0)\ln\frac{v_1}{v_4} \qquad \left[\because \frac{v_2}{v_3} = \frac{v_1}{v_4}\right]$$

$$(COP)_{Ref} = \frac{q_0}{w} = \frac{T_0}{T_k - T_0}$$

$$= \frac{1}{\left(\frac{T_k}{T_0}\right) - 1} = \frac{1}{r^{\gamma-1} - 1} \qquad \left[\because r = \frac{v_1}{v_2} = \frac{v_4}{v_3} = \left(\frac{T_k}{T_0}\right)^{\frac{1}{\gamma-1}}\right]$$

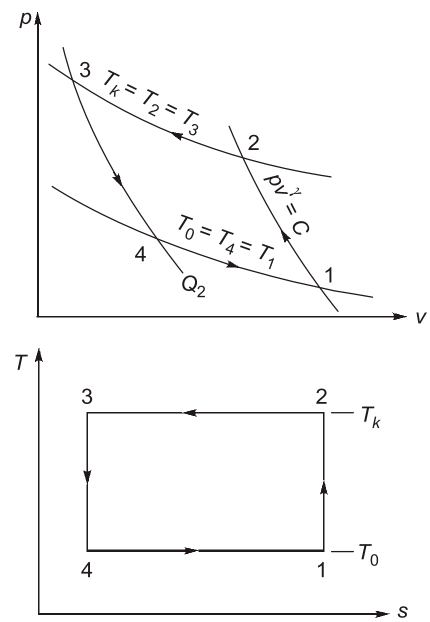



Figure 1.6

### 1.7.1 Draw Back of using Air as Refrigerant in Reversed Carnot Cycle

- Isothermal process of heat absorption and rejection being very slow is not possible.
- *P-v* diagram for gas is very narrow so very high stroke volume is needed to have desired refrigerating effect.

## STUDENT'S ASSIGNMENT

**Q.1** In a certain ideal refrigeration cycle, the COP of heat pump is 5. The cycle under identical conditions running as heat engine will have efficiency as

(a) Zero (b) 0.20
(c) 1.00 (d) 6.00

[IAS : 2001]

**Q.2** The power (kW) required per ton of refrigeration is *N*/COP, where COP is the coefficient of performance, then N is equal to

(a) 2.75 (b) 3.50
(c) 4.75 (d) 5.25

[IAS : 2001]

Q.3 Which one of the following relationships defines Gibb's free energy $G$?
(a) $G = H + TS$ (b) $G = H - TS$
(c) $G = U + TS$ (d) $G = U - TS$
[IAS : 2007]

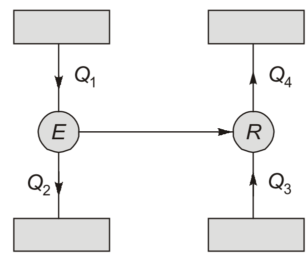
Q.4 In system A vapours are superheated by 10°C in the evaporator while in system B vapours are superheat by 10°C in a liquid vapour regenerative heat exchanger, other conditions being the same. Then
(a) COP of $A$ = COP of $B$
(b) COP of both $A$ and $B$ > COP of reverse Carnot cycle
(c) COP of $A$ > COP of $B$
(d) COP of $A$ < COP of $B$

Q.5 The COP of a refrigerator on a reversed Carnot cycle is 5. The ratio of higher absolute temperature to the lower temperature (i.e., $T_2/T_1$) is
(a) 1.25 (b) 1.3
(c) 1.4 (d) 1.2
[IAS : 2003]

Q.6 A refrigerating machine working on reversed Carnot cycle takes out 2 kW of heat from the system at 200 K while working between temperature limits of 300 K and 200 K. COP and power consumed by the cycle will, respectively, be
(a) 1 and 1 kW (b) 1 and 2 kW
(c) 2 and 1 kW (d) 2 and 2 kW
[IAS : 2004]

Q.7 A refrigerating machine in heat pump mode has a COP of 4. If it is worked in refrigerator mode with power input of 3 kW, what is the heat extracted from the food kept in the refrigerator?
(a) 180 kJ/min (b) 360 kJ/min
(c) 540 kJ/min (d) 720 kJ/min
[IAS : 2006]

Q.8 A refrigerator storage is supplied with 3600 kg of fish at a temperature of 27°C. The fish has to be cooled to –23°C for preserving it for a long period without deterioration. The cooling takes place in 10 hours. The specific heat of fish is 2.0 kJ/kgK above freezing points of fish and 0.5 kJ/kgK below freezing point of fish, which is –3°C. The latent heat of freezing is 230 kJ/kg. What is the power to drive the plant if the actual COP is half that of the ideal COP?
(a) 30 kW (b) 15 kW
(c) 12 kW (d) 6 kW
[IAS : 2002]

Q.9



In the figure shown above, $E$ is the heat engine with efficiency of 0.4 and $R$ is the refrigerator. If $Q_2 + Q_4 = 3Q_1$, the COP of the refrigerator will be
(a) 3.0 (b) 4.5
(c) 5.0 (d) 5.5
[IES : 2014]

Q.10 The refrigeration system of an ice plant working between temperature of –5°C and 25°C produces 20 kg of ice per minute from water at 20°C. The specific heat of water is 4.2 kJ/kg and latent heat of ice is 335 kJ/kg. The refrigeration capacity of the refrigeration plant is
(a) 9040 kJ/min (b) 8750 kJ/min
(c) 8380 kJ/min (d) 8010 kJ/min
[IES : 2017]

Q.11 Operating temperature of a cold storage is –2°C. From the surrounding at ambient temperature of 40°C, heat leaked into the cold storage is 30 kW. If the actual COP of the plant is 1/10 of the maximum COP, then what will be the power required to pump out the heat to maintain the cold storage temperature at –2°C?
(a) 1.9 kW (b) 3.70 kW
(c) 20.28 kW (d) 46.50 kW
[IES : 2009]

Q.12 A heat pump is used to heat a house in the winter and then reversed to cool the house in the summer. The inside temperature of the house is to be maintained at 20°C. The heat transfer through the house wall is 79 kJ/s and the outside temperature in winter is 5°C. What is the minimum power (approximate) required to drive the heat pump?

(a) 40.5 kW (b) 405 kW
(c) 42.5 kW (d) 425 kW

[IES : 2006]

**Q.13** A refrigerator works on reversed Carnot cycle producing a temperature of –40°C. Work done per TR is 700 kJ per ten minutes. What is the value of its COP?

(a) 3 (b) 4.5
(c) 5.8 (d) 7

[IES : 2005]

**Q.14** A reversed Carnot cycle working as a heat pump has COP of 7. What is the ratio of minterm to maximum absolute temperature?

(a) $\frac{7}{8}$ (b) $\frac{1}{6}$

(c) $\frac{6}{7}$ (d) $\frac{1}{7}$

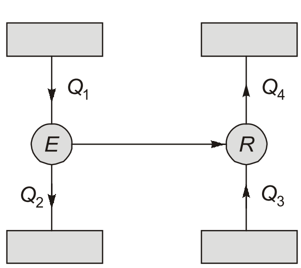
[SSC-JE : 2018]

## ANSWER KEY — STUDENT'S ASSIGNMENT

| | | | | |
|---|---|---|---|---|
| **1.** (b) | **2.** (c) | **3.** (b) | **4.** (d) | **5.** (d) |
| **6.** (c) | **7.** (c) | **8.** (c) | **9.** (c) | **10.** (c) |
| **11.** (d) | **12.** (b) | **13.** (a) | **14.** (c) | |

## HINTS & SOLUTIONS — STUDENT'S ASSIGNMENT

**9. (c)**




$$\eta = 1 - \frac{Q_2}{Q_1} = 0.4$$

$$\Rightarrow \quad \frac{Q_2}{Q_1} = 0.6 \qquad \text{...(i)}$$

$$COP_R = \frac{Q_3}{Q_4 - Q_3} \qquad \text{...(ii)}$$

Given, $Q_2 + Q_4 = 3Q_1$

From equation (i),

$$Q_2 = 0.6Q_1$$

$$\therefore \quad 0.6Q_1 + Q_4 = 3Q_1$$

$$\Rightarrow \quad Q_4 = 2.4Q_1 \qquad \text{...(iii)}$$

From conservation of energy, the work output from engine will be work consumed by efrigerator,

$$Q_1 - Q_2 = W = Q_4 - Q_3$$

$$Q_1 - 0.6Q_1 = Q_4 - Q_3$$

$$0.4Q_1 = 2.4Q_1 - Q_3$$

$$\Rightarrow \quad Q_3 = (2.4 - 0.4)Q_1 = 2Q_1$$

$$\Rightarrow \quad Q_3 = 2Q_1 \qquad \text{...(iv)}$$

From equation (ii), (iii) and (iv),

$$COP = \frac{2Q_1}{2.4Q_1 - 2Q_1} = \frac{2}{0.4}$$

$$COP = 5$$

**10. (c)**

∵ Specific heat of ice is not given so it is assumed that ice is formed at 0°C. Hence refrigeration capacity

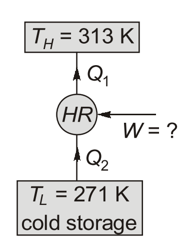
$$= (mC_W\Delta T + mL)$$

$$= 20 \times 4.2 \times 20 + 20 \times 335$$

$$= 8380 \text{ kJ/min}$$

**11. (d)**

To maintain the cold storage temperature –2°C, $Q_2$ must be 30 kW




$$(COP)_{act} = \frac{1}{10} \times (COP)_{max}$$

$$\frac{Q_2}{W} = \frac{1}{10} \times \frac{T_L}{T_H - T_L}$$

$$\frac{30}{W} = \frac{1}{10} \times \left(\frac{271}{313 - 271}\right)$$

$$W = 46.497 \text{ kW}$$