Mechanical Engineering

Refrigeration & Air-Conditioning

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Contents

Refrigeration & Air-Conditioning

Chapter 6

Psychrometry Processes, Air Conditioning, Thermal Comfort and Cooling Load Calculation 67

Chapter 7

Refrigeration Equipment, Duct Design and Methods of Refrigeration 128

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CHAPTER 03

Vapour Absorption Refrigeration Systems

3.1 Introduction

The vapour absorption refrigeration system is one of the oldest methods of producing refrigerating effect. The principle of vapour absorption was first discovered by Michael Faraday in 1824 while performing a set of experiments to liquify certain gases. The first vapour absorption refrigeration machine was developed by a French scientist Ferdinand Carre in 1860. This system can be used in both domestic and large industrial refrigerating plants. The refrigerant commonly used in a vapour absorption system is ammonia.

The vapour absorption system uses heat energy, instead of mechanical energy as in vapour compression systems. In the vapour absorption system, the compressor is replaced by an absorber, a pump, a generator and a pressure reducing valve. These components in the vapour absorption system perform the same function as that of a compressor in the vapour compression system. In this system the vapour refrigerant from the evaporator is drawn into an absorption unit where it is absorbed by the weak solution of the refrigerant forming a strong solution. This strong solution is pumped to the generator where it is heated by some external source. During the heating process, the vapour refrigerant then flows into the evaporator and thus the cycle is completed.

The vapour absorption refrigeration system needs at least two fluids. One fluid acts as a refrigerant while the other as an absorber.

3.1.1 Refrigerant-Solvent Properties

Desirable Properties of (absorber) Solvent

Some of the properties required of a solvent are :

1. The absorber should have great affinity to absorb the refrigerant.
2. Ideal absorbent should remain in liquid state under operating conditions.
3. Heat liberated during the absorption of refrigerant should be as small as possible. This reduces the heat to bee rejected in the absorber.
4. It should have high boiling point.
5. The solvent should have low specific heat for better heat transfer.
6. It should have low viscosity for minimum pump work.

7. There should be a suitable pressure temperature concentration relationship to meet the actual practical conditions needed in the various components of the system.

Desirable Properties of Refrigerant-solvent Combination

1. The desirable absorbent-refrigerant combination should have the property of high solubility at conditions in the absorber but low solubility in the generator.
2. The refrigerant should be more volatile than the absorbent for easy separation in the generator.
3. The combination of refrigerant-absorbent should be chemically stable.
4. Both should not cause corrosion.
5. The refrigerant should have high latent heat to have low mass flow rates.

Characteristics of Ammonia

Ammonia is the most commonly used refrigerant in vapour absorption system for both domestic and industrial applications. It possesses the following properties.

1. Water has large capacity to absorb ammonia vapour, e.g. 1 m^3 of water at 13°C is capable of absorbing 1000 m^3 of ammonia vapour.
2. The amount of NH_3 vapour that water can absorb increases with the increase in pressure and decreases with the increase in temperature.
3. During absorption of ammonia vapour in water, more heat is liberated. It is corrosive to metals.
4. Water can be induced to give up dissolved ammonia by heating since the boiling temperature of ammonia is –33.3°C at atmospheric pressure which is much lower than that of water at any pressure.

Some of the absorption system are discussed in the following sections.

3.2 Simple Vapour Absorption System

Ammonia is used as a refrigerant while water is used as an absorbent. The four components of the vapour compression cycle. Liquid ammonia (normally a mixture of liquid and vapour) from the expansion valve enters the evaporator, either it absorbs heat from the evaporator space or it cools the secondary refrigerant in a heat exchanger. Normally these units have very large cooling capacity of the order of 80 TR and above. In such units, liquid ammonia absorbs heat from the secondary refrigerant which would be used as a medium to cool the space or products in the refrigerated space. Low pressure ammonia vapour then enters the absorber. This vapour is allowed to be mixed and absorbed in the absorber with the weak solution of aqua ammonia flowing from the generator under gravity through a pressure reducing valve. The water has the ability to absorb very large quantities of ammonia vapour and the solution thus formed is known as aqua-ammonia.

The absorption of ammonia vapour in water lowers the pressure in the absorber which in turn draws more ammonia vapour from the evaporator and thus raises the temperature of the solution. Some form of cooling arrangement (usually water cooling) is employed in the absorber to remove the heat of solution evolved in it. This is necessary in order to increase the absorption capacity of water because at higher temperature water absorbs less ammonia vapour. The strong solution thus formed in the absorber is pumped to the generator by a liquid pump. The pump increases the pressure of the solution up to 10 bar.

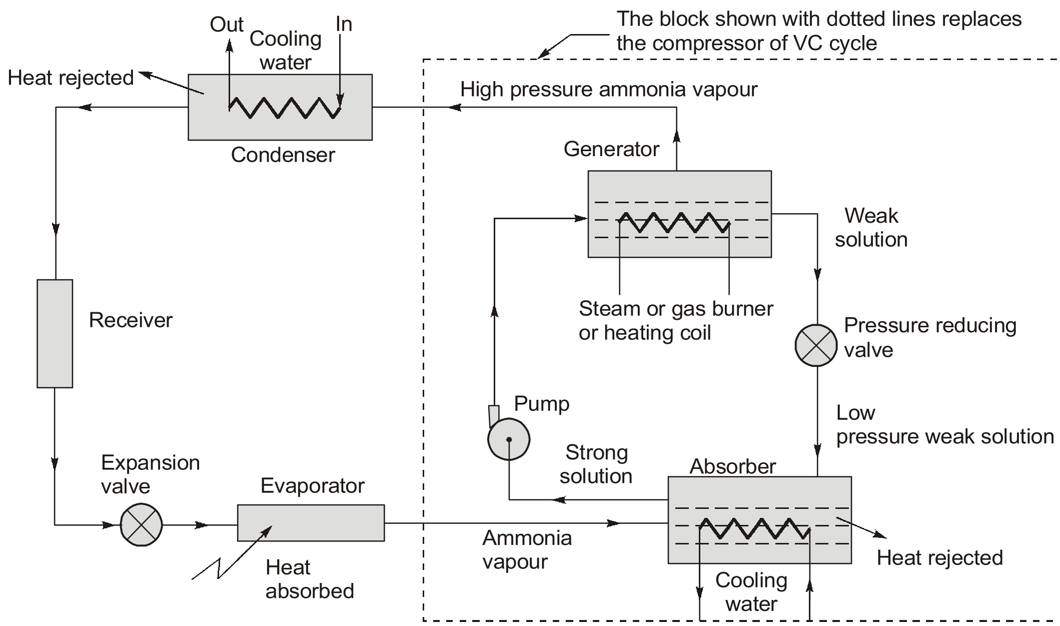

Figure: Simple vapour absorption system

The strong solution of ammonia in the generator is heated by some external source such as gas or steam. During the heating process, the ammonia vapour is driven off the solution at high pressure leaving behind the hot weak ammonia solution in the generator. This weak ammonia solution flows back to the absorber at low pressure after passing through the pressure reducing valve. The high pressure ammonia vapour from the generator is condensed in the condenser to a high pressure liquid ammonia. This liquid ammonia is passed to the expansion valve through the receiver and then to the evaporator. This completes the simple vapour absorption cycle.

The heat required for the operation of generator can be supplied by burning kerosene or using solar energy or waste heat from process industry in the case of industrial applications.

The electrical energy required for the operation of aqua pump in this system is extremely small compared to the electrical energy needed for the compressor of a vapour compression cycle. The basic difference here is that aqua pump handles the liquid ammonia while the compressor has to work with the refrigerant vapour of high specific volume.

3.3 Practical Vapour Absorption System

The working principle of the simple vapour absorption system has been discussed in the previous section. In order to make the system more practical, it is fitted with an analyser, a rectifier and two heat exchangers as shown in figure. These accessories help to improve the performance and working of the plant discussed as follows.

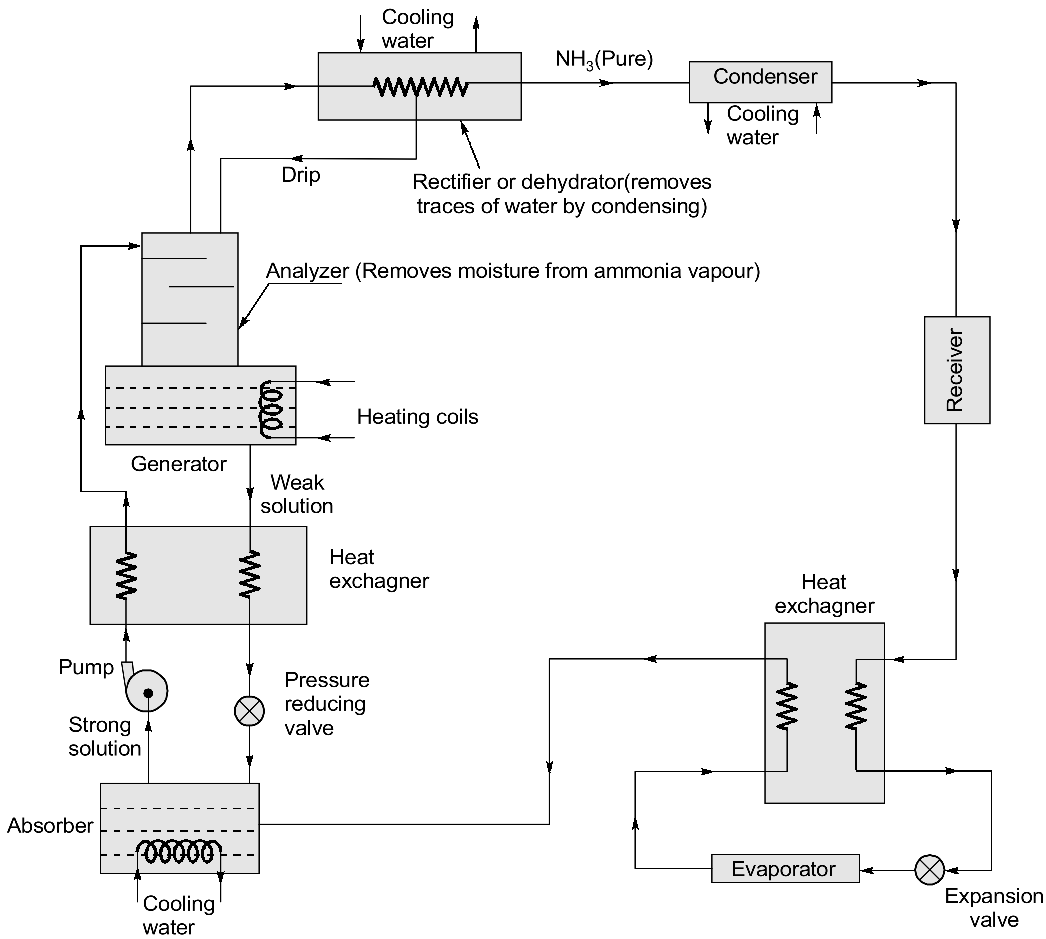

Figure: Block diagram of ammonia-water vapour absorption system

Analyzer : The function of the analyzer is to remove moisture from the ammonia vapour leaving the generator. When ammonia is vaporized in the generator, some water is also vaporized and may flow into the condenser along with the ammonia vapours in the simple system. If these unwanted water particles are not removed before entering into the condenser, they will enter into the expansion valve where they freeze and choke the pipeline. In order to remove these unwanted water particles flowing to the condenser, an analyzer is used. The analyzer may be built as an integral part of the generator or made a separate piece of equipment. It consists of a series of trays mounted above the generator. The strong solution from the absorber and the aqua from the rectifier are introduced at the top of the analyzer and flow downward over the trays and into the generator. In this way, considerable liquid surface area is exposed to the vapour rising from the generator. The vapour is cooled and most of the water vapour condenses, so that mainly the ammonia vapour leaves the top of the analyzer. Since the aqua is heated by the vapour, less external heat is required in the generator.

Rectifier : The function of the rectifier is to condense the leftover traces of water and drain the condensate back to the analyzer, i.e. in case the water vapours are not completely removed in the analyzer, a closed type vapour cooler called rectifier (also known as dehydrator) is used. It is generally water-cooled and may be of the double pipe, shell and coil or shell and tube type. Its function is to further cool the ammonia vapour leaving the analyzer so that the water vapour still remaining in the ammonia vapour, is condensed. Thus, only dry or anhydrous ammonia vapour flows to the condenser. The condensate from the rectifier is returned to the top of the analyzer by a drip return pipe.

Heat Exchangers : The heat exchanger provided between the pump and the generator cools the weak hot solution returning from the generator to the absorber using the cold strong aqua solution supplied by the aqua pump. The heat removed from the weak solution raises the temperature of the strong solution leaving the pump and going to analyzer and generator. This operation reduces the heat supplied to the generator and the amount of cooling required for the absorber. Thus, the economy of the plant increases.

The heat exchanger provided between the condenser and the evaporator may also be called liquid subcooler. In this heat exchanger, the liquid refrigerant leaving the condenser is sub-cooled by the low temperature ammonia vapour from the evaporator as shown in figure. This subcooled liquid is now passed to the expansion valve and then to the evaporator.

In this system, the net refrigerating effect is the heat absorbed by the refrigerant in the evaporator. The total energy supplied to the system is the sum of the work done by the pump and the heat supplied in the generator. Therefore, the coefficient of performance of the system is given by

$$\text{COP} = \frac{\text{Heat absorbed in evaporator}}{\text{Work done by pump + Heat supplied in generator}}$$

3.4 Vapour Absorption Refrigeration System Vs Vapour Compression Refrigeration System

Following are the advantages of the vapour absorption system over the vapour compression system :

1. In the vapour absorption system, the only moving part of the entire system is a pump which has a small motor. Thus, the operation of this system is essentially quiet and subjected to little wear. The vapour compression system of the same capacity has more wear, tear and noise due to moving parts of the compressor.
2. The vapour absorption system uses heat energy to change the condition of the refrigerant from the evaporator. The vapour compression system uses mechanical energy to change the condition of the refrigerant from the evaporator.
3. The vapour absorption systems are usually designed to use steam, either at high pressure or low pressure. The exhaust steam from furnaces and solar energy may also be used. Thus, this system can be used where the electric power is difficult to obtain or is very expensive.
4. The vapour absorption systems can operate at reduced evaporator pressure and temperature by increasing the steam pressure to the generator with little decrease in the capacity. But the capacity of a vapour compression system drops rapidly with lowered evaporator pressure.
5. The load variations do not affect the performance of a vapour absorption system. The load variations are met by controlling the quantity of aqua circulated and the quantity of steam supplied to the generator. The performance of a vapour compression system at partial loads is, however, poor.
6. In the vapour absorption system, the liquid refrigerant leaving the evaporator has no bad effect on the system except that of reducing the refrigerating effect. In the vapour compression system, it is essential to superheat the vapour refrigerant leaving the evaporator so that no liquid may enter the compressor.
7. The vapour absorption systems can be built in capacities well above 1000 TR of refrigeration. The same is not the case with the vapour compression cycle using compressors.
8. The space requirements and automatic control requirements favour the absorption . - system more as the desired evaporator temperature drops.

3.5 COP of an Ideal Vapour Absorption Refrigeration System

The objective of the refrigerator is to remove heat (Q_L) from the cold space. To accomplish this, it needs energy input. Therefore, the COP of a refrigerator is

$$COP_R = \frac{\text{Desired effect}, Q_L}{\text{Energy input}}$$

Q_L is absorbed by the refrigerant in the evaporator.

The energy input in an absorption refrigeration system includes :

1. The heat Q_g given to the refrigerant in the generator, and
2. The heat Q_P added to the refrigerant due to pump work as shown in figure.

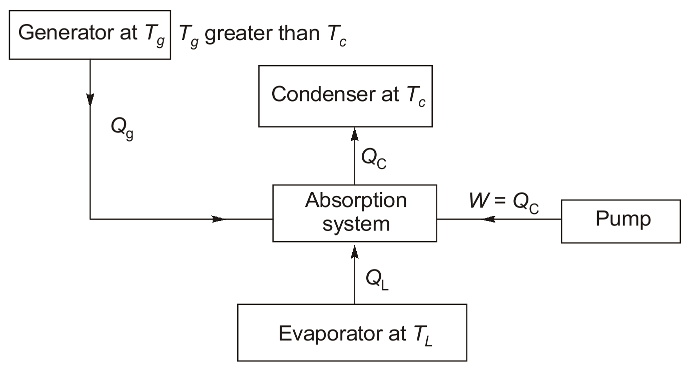

Figure: Theoretical COP of the vapour absorption system

Let Q_C be the heat dissipated to the atmosphere or cooling water from the condenser and absorber.

According to the first law of thermodynamics,

$$Q_C = Q_g + Q_L + Q_P$$

Since the heat due to pump work Q_P is very negligible,

$$Q_C = Q_g + Q_L \qquad \text{. . . (3.1)}$$

Let,

T_g be the temperature at which heat Q_g is supplied to the generator

T_C be the temperature at which heat Q_C is discharged to atmosphere or cooling water from the condenser and absorber

T_L be the temperature at which heat Q_L is absorbed in the evaporator.

Since the vapour absorption system can be considered as a perfectly reversible system, the initial entropy of the system must be equal to the entropy of the system after the change in its condition.

$$\therefore \quad \frac{Q_g}{T_g} + \frac{Q_L}{T_L} = \frac{Q_C}{T_C}$$

From equation (3.1), we can write

$$\frac{Q_C}{T_C} = \frac{Q_g + Q_L}{T_C}$$

or

$$\frac{Q_g}{T_g} - \frac{Q_g}{T_C} = \frac{Q_L}{T_C} - \frac{Q_L}{T_L}$$

or

$$Q_g\left(\frac{T_C - T_g}{T_g \times T_C}\right) = Q_L\left(\frac{T_L - T_C}{T_C \times T_L}\right)$$

or
$$Q_g = Q_L\left(\frac{T_L - T_C}{T_C \times T_L}\right)\left(\frac{T_g \times T_C}{T_C - T_g}\right) = Q_L\left(\frac{T_C - T_L}{T_C \times T_L}\right)\left(\frac{T_g \times T_C}{T_g - T_C}\right)$$

$$= Q_L\left(\frac{T_C - T_L}{T_L}\right)\left(\frac{T_g}{T_g - T_C}\right) \quad \text{. . . (3.3)}$$

The maximum coefficient of performance (COP) of the system is given by

$$(COP)_{max} = \frac{Q_L}{Q_g} = \left(\frac{T_L}{T_C - T_L}\right)\left(\frac{T_g - T_C}{T_g}\right) \quad \text{. . . (3.4)}$$

In equation (3.4)

1. The expression $\left(\frac{T_L}{T_C - T_L}\right)$ represents the COP of a Carnot refrigerator working between the temperature limits of T_L and T_C.
2. The expression $\left(\frac{T_g - T_C}{T_g}\right)$ represents the efficiency of a Carnot engine working between the temperature limits of T_g and T_C.

Thus, a theoretical or an ideal vapour absorption refrigeration system may be regarded as a combination of a Carnot engine and a Carnot refrigerator. The maximum COP may be written as :

$$(COP)_{max} = (COP)_{Carnot} \times \eta_{Carnot}$$

Example 3.1 **In a vapour absorption refrigeration system, heat addition in the generator is at 90°C, heat rejection is at 30°C, and refrigeration takes place at the temperatures of –5°C. Find the maximum COP of the system.**

Solution:

Given:
$$T_g = 90°C = 90 + 273 = 353 \text{ K};$$
$$T_C = 30°C = 30 + 273 = 303 \text{ K};$$
$$T_L = -5°C = -5 + 273 = 268 \text{ K}$$

We know that the maximum COP of the system is

$$= \left(\frac{T_L}{T_C - T_L}\right)\left(\frac{T_g - T_C}{T_g}\right) = \left(\frac{268}{303 - 268}\right)\left(\frac{353 - 303}{353}\right) = 1.079$$

One question that comes to our mind is : what is significance of solving this example? Let us assume that a very large capacity ammonia vapour absorption refrigeration system is working. We know only three temperatures. With such a data under ideal conditions, the unit can produce a refrigeration effect at the rate of 1 kW at –5°C, consuming energy at the rate of 1 kW. One can also make a rough estimate that if the actual COP of the system is 50% of the maximum COP, the unit can produce cooling effect at the rate 1 kW for every 2 kW energy input. One can make a rough estimate of the COP of the system for the varying operating temperatures of T_g, T_C and T_L.

Example 3.2 In an absorption type refrigerator, the heat is supplied to NH_3 generator by condensing steam at 1.6 bar and 80% dry. The temperature in the refrigerator is to be maintained at –5°C. Find the maximum COP possible.

If the refrigeration load is 150 TR and the actual COP is 80% of the maximum COP, find the mass of the steam required per hour. Take the temperature of the atmosphere to be 30°C.

Solution:

Given:

$$P = 1.6 \text{ bar};\ x = 80\% = 0.8;$$
$$T_L = -5°C = -5 + 273 = 268 \text{ K};$$
$$Q = 150 \text{ TR};$$
$$\text{Actual COP} = 80\% \text{ of maximum COP};$$
$$T_C = 30°C = 30 + 273 = 303 \text{ K}$$

Maximum COP

It is interesting to ask one question here as to why is steam considered wet steam and not dry saturated or superheated one. The answer is, that steam is not generated in the boiler specifically to run the absorption refrigeration unit. Heat energy from the steam available from the process industry as a waste, or that available from the outlet of the steam turbine, is used for absorption refrigeration. The condition of steam from such a source is normally of this order. So, wet steam is assumed here.

From steam tables, we find that the saturation temperature of steam at a pressure of 1.6 bar is

$$T_g = 113.3°C = 113.3 + 273 = 386.3 \text{ K}$$

We know that maximum COP

$$= \left(\frac{T_L}{T_C - T_L}\right)\left(\frac{T_g - T_C}{T_g}\right) = \left(\frac{268}{303-268}\right)\left(\frac{386.3-303}{386.3}\right) = 1.417$$

Mass of steam required per hour:

We know that actual COP

$$= 0.8 \text{ of maximum COP} = 0.8 \times 1.417 = 1.133$$

$$\therefore \quad \text{Actual heat supplied} = \frac{\text{Refrigeration load}}{\text{Actual COP}} = \frac{150 \times 3.5167}{1.133} = 465.5 \text{ kW}$$

Assuming that only latent heat of steam is used for heating purposes, therefore from steam tables, the latent heat of steam at 1.6 bar is

$$h_{fg} = 2220.9 \text{ kJ/kg}$$

$\therefore$ Mass of steam required per hour

$$= \frac{\text{Actual heat supplied}}{h_{fg}} = \frac{465.5}{2220.9}$$

$$= 0.232 \text{ kg/s} = 838 \text{ kg/h}$$

Example 3.3 (a) In a vapour absorption system, the heating, cooling and refrigeration temperatures are 115°C, 30°C and –10°C, respectively. Find the COP of the system.

(b) In case the heating temperature is increased to 200°C and the refrigeration temperature is reduced to –30°C with cooling temperature remaining the same, find the new COP and percentage change in COP.

Solution:

(a) Given:

$$T_g = 115°C = 115 + 273 = 388 \text{ K}$$
$$T_C = 30°C = 30 + 273 = 303 \text{ K}$$
$$T_L = -10C = -10 + 273 = 263 \text{ K}$$

$$\text{COP} = \left(\frac{T_L}{T_C - T_L}\right) \times \left(\frac{T_g - T_C}{T_g}\right)$$

$$= \left(\frac{263}{303 - 263}\right) \times \left(\frac{388 - 303}{388}\right) = 1.44$$

(b) Given:

$$T_{g1} = 200°C = 200 + 273 = 473 \text{ K},$$
$$T_{C1} = T_C = 30°C = 303 \text{ K}$$
$$T_{L1} = -10°C = -10 + 273 = 263 \text{ K}$$

$$(\text{COP})_1 = \left(\frac{T_{L_1}}{T_{C_1} - T_{L_1}}\right) \times \left(\frac{T_{g_1} - T_{C_1}}{T_{g_1}}\right)$$

$$= \left(\frac{263}{303 - 263}\right) \times \left(\frac{473 - 303}{473}\right) = 2.363$$

Here, the temperature of the heat source is increased from 115°C to 200°C because of which COP had jumped from 1.44 to 2.363. It indicates that the temperature at which heat is supplied to the generator has a commendable effect on the performance of the unit.

3.6 Domestic Electrolux (Ammonia -Hydrogen) Refrigerator

The 'Electrolux Company' of Luton, England first developed this Domestic Electrolux (Ammonia-Hydrogen) Refrigerator.

This type of refrigerator is called three fluids absorption system. Three fluids are, namely ammonia, hydrogen and water. Ammonia acts as a refrigerant, water as an absorbent and hydrogen gas promotes evaporation of refrigerant in the evaporator. hydrogen does not react with ammonia and water. The main purpose of this system is to eliminate the pump so that in the absence of moving parts, the machine becomes noiseless.

The principle of operation of a domestic Electrolux type refrigerator, as shown in figure. The strong ammonia solution is heated in the generator by applying heat from an external source, usually a gas burner. Due to heating process, ammonia vapours are removed from the solution and passed to the condenser. A rectifier or a water separator fitted before the condenser removes water vapour carried with the ammonia vapours so that dry ammonia vapours are supplied to the condenser. These water vapours, if not removed, will enter into the evaporator causing freezing and choking of the machine. The hot weak solution left behind in the generator flows to the absorber through the heat exchanger. This hot weak solution while passing through the exchanger is cooled. The heat removed by the weak solution is utilized in raising the temperature of the strong solution passing through the heat exchanger. In this way, the absorption is accelerated and improvement in the performance of a plant is achieved.

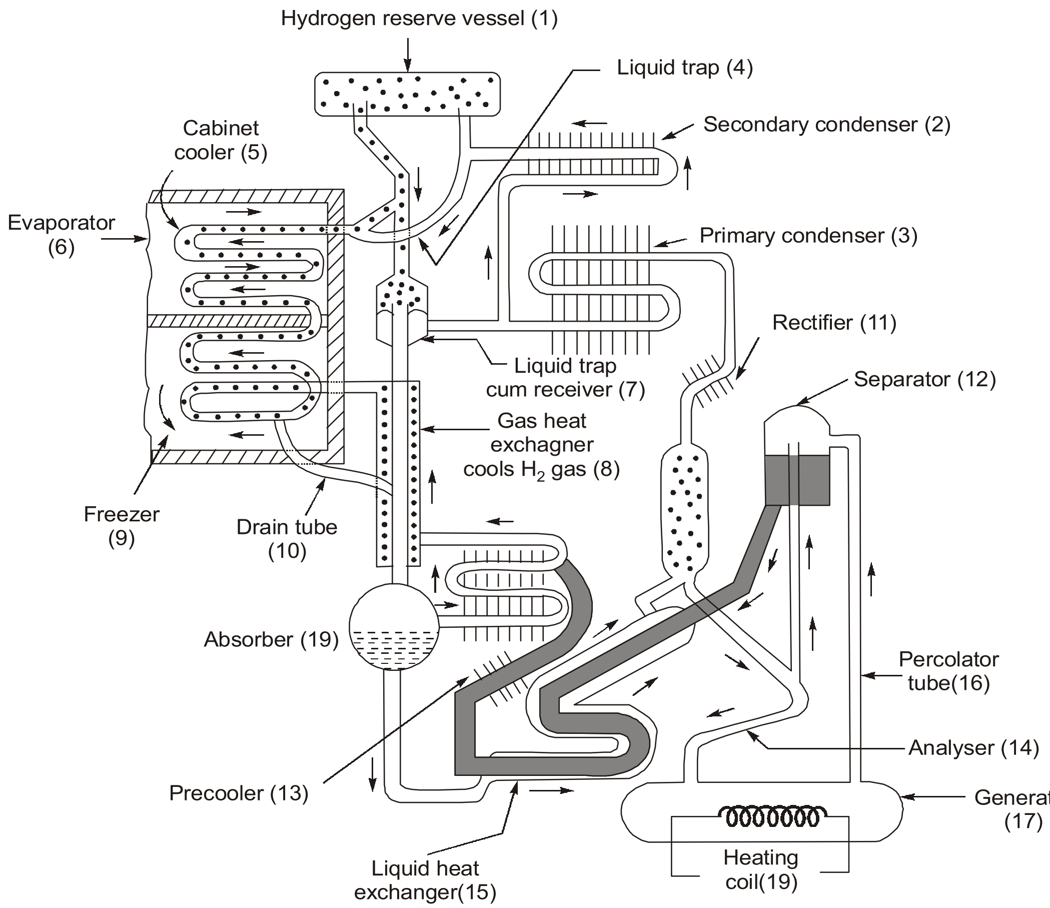

Figure: Block diagram of Electrolux refrigerator

The ammonia vapours in the condenser are condensed by using an external cooling source. The liquid refrigerant leaving the condenser flows under gravity to the evaporator where it meets the hydrogen gas. The hydrogen gas which is being fed to the evaporator permits the liquid ammonia to evaporate at a low pressure and temperature according to Dalton's principle. During the process of evaporation, the ammonia absorbs latent heat from the refrigerated space and thus produces cooling effect.

The mixture of ammonia vapour and hydrogen is passed to the absorber where ammonia is absorbed in water while the hydrogen rises to the top and flows back to the evaporator. This completes the cycle. The coefficient of performance of this refrigerator is given by

$$\text{COP} = \frac{\text{Heat absorbed in the evaporator}}{\text{Heat supplied in the generator}}$$

Note:

1. The hydrogen gas only circulates from the absorber to the evaporator and back.
2. The whole cycle is carried out entirely by gravity flow of the refrigerant.
3. It cannot be used for industrial purposes as the COP of the system is very low.

Objective Brain Teasers

Q.1 COP of practical vapour compression system as compared to that for vapour absorption system is
(a) More
(b) Less
(c) Unpredictable
(d) More for sub-zero temperature and less for temperature above zero

Q.2 Electrolux refrigerator has the following working substances
(a) H_2
(b) NH_3 and H_2
(c) NH_3, H_2 and H_2O
(d) NH_3 and H_2O

Q.3 Electrolux system of refrigeration has
(a) Only one liquid pump
(b) Only two liquid pumps
(c) No liquid pump
(d) None of the above

Q.4 The function of a compressor in a vapour absorption system is performed by the
(a) Absorber
(b) Absorber and pump
(c) Pump and generator
(d) Absorber, pump and generator

Q.5 Absorption system normally uses the following refrigerant
(a) R-11 (b) R-22
(c) CO_2 (d) Ammonia

Q.6 The refrigerant used for absorption refrigerators working from solar collectors is a mixture of water and
(a) CO_2 (b) SO_2
(c) Li-Br (d) R-12

Q.7 Which of the following is not a desirable characteristic of ideal absorbent in vapour absorption system?
(a) high affinity for the refrigerant
(b) low boiling point
(c) low specific heat
(d) chemical stability

Q.8 Absorbent in a vapour absorption refrigerator system separates from the refrigerant only when it
(a) is sufficiently heated
(b) is sprayed on cooling water
(c) is cooled
(d) reacts with refrigerant

ANSWERS

1. (a)	2. (c)	3. (c)	4. (d)	5. (d)
6. (c)	7. (b)	8. (a)		

Student's Assignments

Q.1 How does an absorption refrigeration system differ from a mechanical refrigeration system?

Q.2 How was the concept of vapour absorption system generated? Explain briefly.

Q.3 Enumerate the desirable properties of solvent and refrigerant-solvent combination for the vapour absorption system.

Q.4 Explain the working of a simple ammonia-water absorption refrigeration system with the help of a neat sketch.

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