COURSE CODE:	*MCE 407*
COURSE TITLE:	*Refrigeration & Air-Conditioning I*
NUMBER OF UNITS:	*3 Units*
COURSE DURATION:	*Three hours per week*

COURSE DETAILS:

Course Coordinator:	**Engr. Dr. Bukola Olalekan Bolaji** *B.Eng., M.Eng., PhD*
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Other Lecturers:	**None**

COURSE CONTENT:

Fundamental of vapour compression refrigeration. Analysis of refrigeration cycles. Heat pumps. Refrigerants and their properties. Absorption refrigeration. Principles of air-conditioning with emphasis on thermodynamic processes involving air-water-vapour mixture. Production of atmospheric and thermal-environments for human activity. Principles of cooling, freezing and storing of perishable products.

COURSE REQUIREMENTS:

This is a compulsory course for all 400 level students in the Department of Mechanical Engineering. In view of this, students are expected to participate in all the course activities and have minimum of 75% attendance to be able to write the final examination.

READING LIST:

1. Bolaji BO. Refrigerants and stratospheric ozone: past, present and future. In: Okoko E, Adekunle VAJ (Eds), Environmental Sustainability and Conservation in Nigeria. Jubilee, Akure, Nigeria, 2005, pp. 231-239.
2. Bolaji BO. Experimental analysis of reciprocating compressor performance with eco-friendly refrigerants. Proc. IMechE, Part A: Journal of Power and Energy 2010;224:781-786.
3. Dincer I. Refrigeration Systems and Applications. England: John Wiley and Sons, Ltd., 2003.
4. Dossat RJ, Horan TJ. Principles of Refrigeration, Prentice-Hall International Inc., New Jersey, USA, 2002.
5. ASHRAE, Refrigeration Handbook. Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers. Atlanta, GA: ASHRAE, Inc., 1998.
6. ASHRAE. Thermophysical Properties of Refrigerants. Atlanta, GA: ASHRAE Fundamental, Inc., 2001; pp. 20:1-67.

LECTURE NOTES

1.0 PRINCIPLE & APPLICATION OF REFRIGERATION

Definition: Refrigeration is defined as the branch of science that deals with the process of reducing and maintaining the temperature of a space or material below the temperature of the surroundings.

- The purpose of refrigerator is to transfer heat from a cold chamber which is at a temperature lower than that of its surroundings.
- The natural flow of heat from the surroundings back to the cold chamber can be resisted by insulating the chamber from the surroundings.

HEAT PUMP

- This energy rejection in the refrigeration system must be carried out at a temperature above that of the surroundings.
- This energy can be used for heating purposes and refrigerating plants designed entirely for this purpose are called *heat pumps*.

Definition Heat pump is the, transferring of energy against the natural temperature gradient from a low – temperature to a higher one. It is analogous to pumping of water from a low level to a higher one against the natural gradient of gravitational force.

REFRIGERATION AND HEAT PUMP

- There is no difference in operation between a refrigerator and a heat pump.
- With the refrigerator the important quantity is the energy removed from cold chamber called the refrigerating effect, and
- With the heat pump it is the energy to be rejected by the refrigerant for heating purposes.
- The machine can be used for both purposes

NEED FOR THERMAL INSULATION

- Heat will always migrate from a region of high temperature to a region of lower temperature, there is always a continuous flow of heat into the refrigerated region from the warmer surrounding.
- To limit the flow of heat into the refrigerated region to some practical minimum, it is usually necessary to isolate the region from its surroundings with a good heat-insulating material.

THE REFRIGERATION LOAD

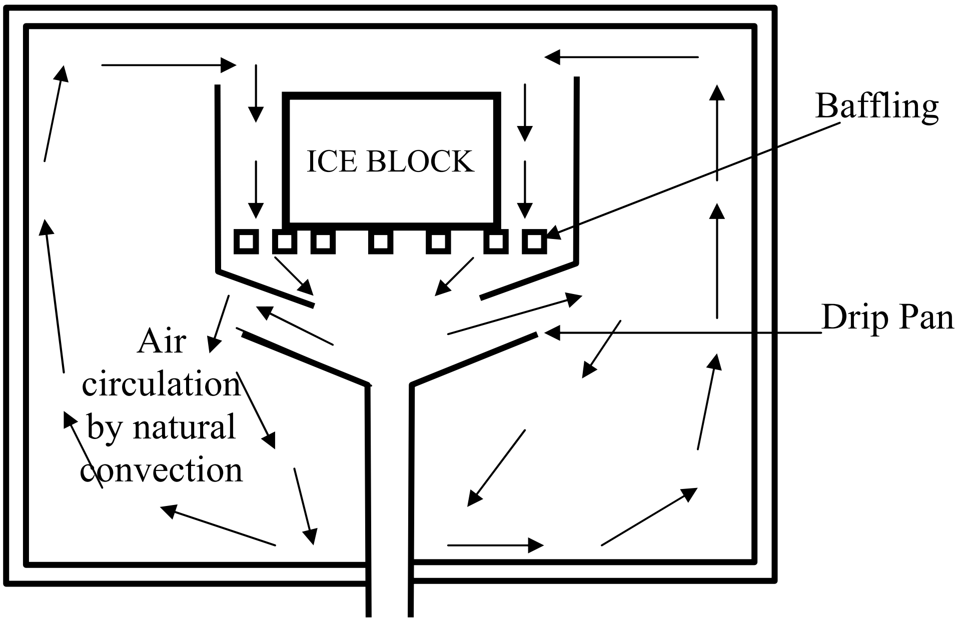
The rate at which heat must be removed from the refrigerated space or material in order to produce and maintain the desired temperature conditions is called the refrigeration load, the cooling load, or the heat load.

Sources of Cooling Load:

a) The heat transmitted by conduction through the insulated walls.
b) The heat that must be removed from the warm air that enters the space through opening and closing doors.
c) The heat that must be removed from the refrigerated product to reduce the temperature of the product to the storage temperature;

d) The heat given off by people working in the space and by motors, lights and other heat-producing equipment operating in the space.

ICE REFRIGERATOR



Disadvantages of using Ice as a Refrigerant

a) It is not possible to obtain temperature lower than 0°C.
b) It is necessary to be replenishing the supply of ice frequently; this practice is neither convenient nor economical.
c) More obvious disadvantage of ice is the problem of disposing of the water resulting from the melting of the ice.
d) The difficulty experienced in controlling the rate of refrigeration, which in turn makes it difficult to maintain the desired low temperature level within the refrigerated space.

APPLICATIONS OF REFRIGERATION

Refrigeration applications may be grouped into six general categories:

a) domestic refrigeration
b) commercial refrigeration
c) industrial refrigeration
d) marine & transportation refrigeration
e) comfort air conditioning
f) industrial air conditioning.

DOMESTIC REFRIGERATION

Domestic refrigeration is rather limited in scope, being concerned primarily with household refrigerators and home freezers. However, because the number of units in service is quite large, domestic refrigeration represents a significant portion of the refrigeration industry.

COMMERCIAL REFRIGERATION

Commercial refrigeration is concerned with the designing, installation, and maintenance of refrigerator used by retail stores; restaurants, hotels, and institutions for the storing and dispensing of perishable commodities of all types.

INDUSTRIAL REFRIGERATION.

- Industrial is often confused with commercial refrigeration because the division between these two areas is not clearly defined.
- Industrial refrigeration is larger in size than that of commercial and has the distinguishing feature of requiring an attendant on duty; usually a licensed operating engineer.
- Typical industrial applications are ice plants, large food-packing plants, breweries, creameries, and industrial plants.

MARINE REFRIGERATION

Marine refrigeration refer to aboard marine vessels and includes, for example, refrigeration for fishing boats and for vessels transporting perishable cargo as well as refrigeration for the ships stores on vessels of all kinds.

TRANSPORTATION REFRIGERATION

Transportation refrigeration is concerned with refrigeration equipment as it is applied to trucks, both long distance transports and local delivery, and to refrigerated railway cars.

PRESERVATION BY REFRIGERATION

- The preservation of perishables by refrigeration involves the use of low temperature as a means of eliminating or retarding the activity of spoilage agents.
- The storage of perishable at low temperatures greatly reduces the activity of both enzymes and micro-organisms and thereby provides a practical means of preserving perishables in their original fresh state for varying periods of time.
- Preservation of food products can be grouped into two general categories:

Preservation of Living Food

- The preservation problem of living food substances is chiefly one of keeping the food substance alive while at the same time retarding natural enzymic activity in order to slow the rate of maturation or ripening.
- Vegetables and fruit are as much alive after harvesting as they are during the growing period due to the utilization of the previously stored food substances.
- This causes the vegetable or fruit to undergo changes, which will eventually result in deterioration and complete decay of the product.
- The primary purpose of placing such products under refrigeration is to slow the living processes by retarding enzymic activity, thereby keeping the product in a preserved condition for a longer period.

Preservation of Non-Living Food

- Non-living food substances, such as meat, poultry, and fish, are much more susceptible to microbial contamination and spoilage than are living food substances, and they usually require more stringent preservation methods.
- The problem of preservation of non-living food substances is one of protecting dead tissue from all the forces of putrefaction and decay both enzymic and microbial.
- The enzymes causing the most trouble are those which catalyze hydrolysis and oxidation and are associated with the breakdown of animal fats.

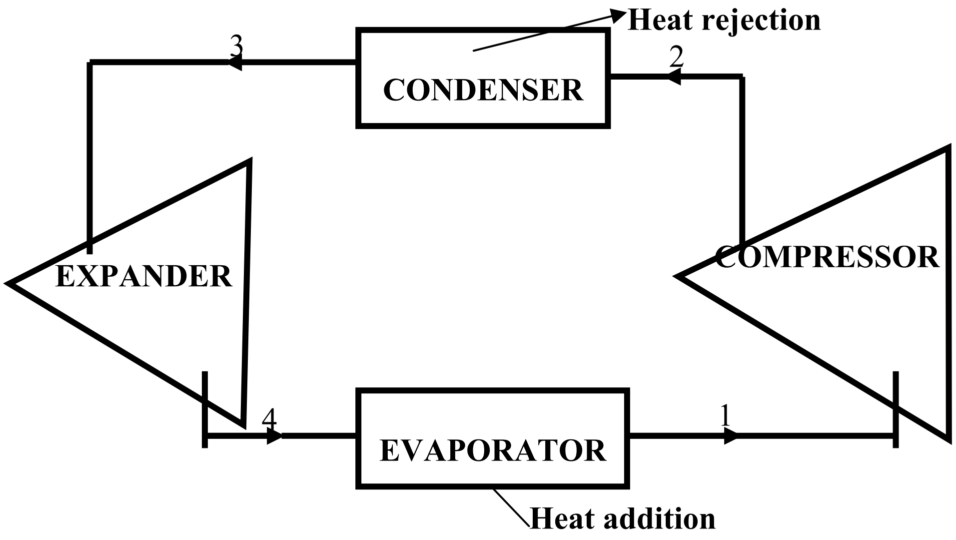
2.0 VAPOUR COMPRESSION REFRIGERATION

The vapour compression cycle is the most widely used refrigeration cycle in practice. In this cycle a vapour is compressed, then condensed to a liquid, and the pressure is dropped so that fluid can evaporate at a low pressure.

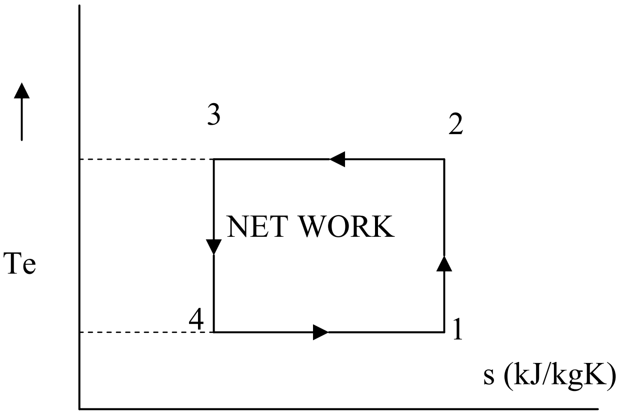
CARNOT REFRIGERATION CYCLE.

The Carnot cycle is one whose efficiency cannot be exceeded when operating between two given temperatures. The Carnot heat engine receives energy at a high level of temperature, converts a portion of the energy into work, and discharges the remainder to a heat sink at a low level of temperature.

The Carnot refrigeration cycle performs the reverse effect of the heat engine, because it transfers energy from a low level of temperature to a high level of temperature. The diagram of the equipment and the temperature – entropy diagram of the refrigeration cycle are shown below.



Carnot Refrigeration Cycle.



Temperature – Entropy diagram of the Carnot Refrigeration Cycle.

The processes that constitute the cycle are:
Process 1 – 2 Isentropic compression, $S_1 = S_2$
Process 2 – 3 Isothermal rejection of heat at Tc = Constant i.e. $T_2 = T_3$.
Process 3 – 4 Isentropic expansion, $S_3 = S_4$.
Process 4 – 1 Isothermal addition of heat (heat absorption from the cold reservoir) at Te = constant i.e $T_1 = T_4$.

All the processes in the Carnot cycle are thermodynamically reversible. Processes 1 –2 and 3 – 4 are consequently reversible adiabatic (isentropic).

The withdrawal of heat from the low temperature source in process 4 –1 is the refrigeration step and is the entire purpose of the cycle. All the other processes in the cycle function so that the low – temperature energy can be discharged to some convenient high – temperature sink.

The Carnot cycle, consists of reversible process which make its efficiency higher than could be achieved in an actual cycle. Although Carnot cycle is an unattainable ideal cycle, it necessary to study the cycle because of the following reasons.

(i) It serves as a standard of comparison, and
(ii) It provides a convenient guide to the temperatures that should be maintained to achieve maximum effectiveness.

COEFFICIENT OF PERFORMANCE.

Before any evaluation of the performance of a refrigeration system can be made, an effectiveness term must be defined. The index of performance is not called efficiency, however, because that term is usually reserved for the ratio of output to input. The ratio of output to input would be misleading applied to a refrigeration system because the output in process 2-3 (fig. 2.1) is usually wasted. The concept of the performance index of the refrigeration cycle is the same as efficiency. The performance term in the refrigeration cycle is called the coefficient of performace; defined as

$$\text{Coefficient of Performance} = \frac{\text{Useful refrigeration}}{\text{Net Work.}}$$

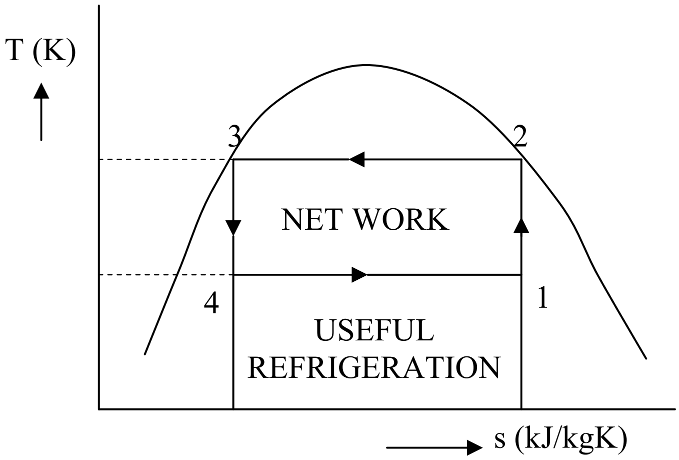
Or

$$COP_{ref} = \frac{\text{Refrigerating Effect}}{\text{Net Work.}}$$

The two terms which make up the coefficient of performance must be in the same units, so that the coefficient of performance is dimensionless.

The heat transferred in a reversible process is : $Qrev = \sum Tds$. Areas beneath reversible processes on the temperature – entropy diagram therefore represent transfers of heat. Area shown in Fig. 2.2 can represent the amount of useful refrigeration and network. The useful refrigeration is the heat transferred in process 4 –1, or the area beneath line 4 –1. The area under line 2 –3 represents the heat rejected from the cycle and heat added to the cycle is the net heat which for a cyclic process equals the network. The area enclosed in rectangle 1-2-3-

4 represents the network. An expression for the coefficient of performance of the Carnot refrigeration cycle is therefore;



T – s diagram of the Carnot Cycle showing useful Refrigeration and Net Work.

$$COP_{ref} = \frac{\text{Useful Refrigeration}}{\text{Net Work}} = \frac{T_1(S_1 - S_4)}{T_2(S_2 - S_3) - T_1(S_1 - S_4)}$$

$S_2 - S_3 = S_1 - S_4$ Since $S_2 = S_1$ and $S_3 = S_4$.

Therefore $$COP_{ref} = \frac{T_1(S_1 - S_4)}{(T_2 - T_1)(S_1 - S_4)} = \frac{T_1}{T_2 - T_1}$$

Or $$COP_{ref} = \frac{Te}{Tc - Te}$$

Where Te = temperature in the evaporator
Tc = temperature in the condenser.

For Heat Pump

$$COP_{hp} = \frac{\text{Heat rejected from the Cycle}}{\text{Net Work}}$$

$$COP_{hp} = \frac{T_2(S_2 - S_3)}{T_2(S_2 - S_3) - T_1(S_1 - S_4)}$$

$$COP_{hp} = \frac{T_3}{T_1 - T_2} \quad \text{or} \quad \frac{Tc}{Tc - Te}$$

The coefficient of performance of the Carnot cycles is entirely a function of the temperature limits and vary from zero to infinity.

CONDITIONS FOR HIGHEST COEFFICIENT OF PERFORMANCE.

A low value of Tc will make the coefficient of performance high. A high value of Te increases the numerator and decreases the denominator, both of which increase the coefficient of performance. The value of Te, therefore, has a more pronounced effect upon the coefficient of performance than Tc.

EXAMPLE

The temperature in a refrigerator evaporator coil is - 6 ^{o}C and that in the condenser coil is 22^{o}C. Assuming that the machine operates on these reversed Carnot cycle, calculate

(i) the COP_{ref},
(ii) the refrigerating effect per kilowatt of input work, and
(iii) the heat rejected to the condenser.

SOLUTION.

Te = - 6 ^{0}C = 273 – 6 = 267K;
Tc = 22^{0}C = 273 + 22 = 295K
Work input (W) = 1kW

(i) $COP_{ref} = Te / (Tc - Te) = 267 / (295 - 267) = 267 / (28)$
$= 9.54$

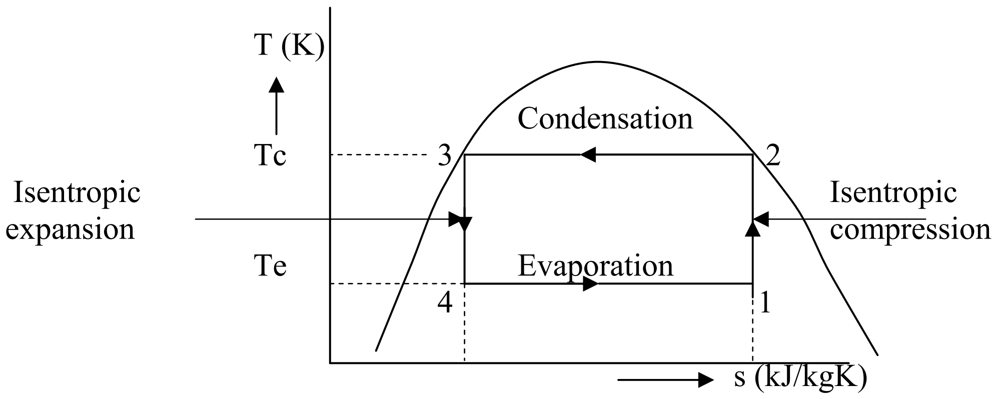
(ii) $COP_{ref} = \frac{\text{Refrigerating Effect}}{\text{Work Input}} \quad \frac{Qe}{W}$

Refrigerating Effect $= COP_{ref} \times$ Net Work
$= 9.54 \times 1$kW
$= 9.54$ kW

(iii) Heat rejected at condenser Qc is equal to the sum of heat absorbed from the evaporator Qe and work input W
i. e. Qc = Qe + W
Qc = 9.54kW + 1kW
Qc = 10.54Kw

VAPOUR AS A REFRIGERANT IN REVERSED CARNOT CYCLE.

The reversed Carnot cycle can be made almost completely practical by operating in the liquid – vapour region of a pure substance as shown below.



Reversed Carnot Cycle with Vapour as a Refrigerant.

The isothermal processes of heat rejection (2 – 3) and heat absorption (4 – 1) of the Carnot cycle are achieved by making use of the phenomena of condensation and evaporation of a pure substance at constant pressure and temperature. This alternate condensation and evaporation of a working substance is accompanied by alternate isentropic compression (1-2) and expansion (3 –4) processes. It may be noted that the vapour during compression is wet although it is dry-saturated at the end of compression. Such a compression is called ***wet compression***. It may also be seen that the isentropic expansion of the liquid from 3 to 4 results in flashing of the refrigerant with a consequent temperature drop from Tc to Te. But such an expansion of a liquid with partial vaporization is practically difficult to achieve in a fast – moving piston and cylinder mechanism.

The thermodynamic analysis per unit mass of the refrigerant is given below.

Refrigerating effect, $Qe = h_1 - h_4$
Heat rejected, $Qc = h_2 - h_3 = (h_{fg})c$
Compressor work, $Wcp = h_2 - h_1$
Expander Work, $Wex = h_3 - h_4$
Net work, $W = Wcp - Wex$
$W = (h_2 - h_1) - (h_3 - h_4)$
$W = Qc - Qe$
$= (h_2 - h_3) - (h_1 - h_4)$

$$COP_{ref} = \frac{Qe}{W} = \frac{Qe}{Qc - Qe} = \frac{h_1 - h_4}{(h_2 - h_3) - h_1 - h_4)}$$

EXAMPLE

A Carnot refrigerator has working temperatures of - 30°C and 35°C. If it operates with R12 as a working substance, calculate the work of isentropic compression, the work of isentropic expansion, refrigerating effect and heat rejected per kg of the refrigerant, and COP of the Cycle.

SOLUTION

Referring to Fig. 2.3, from the table of properties of R12, we have

at 35°C $s_f = s_3 = s_4 = 0.2559 kJ/kg.K$
$s_g = s_2 = s_1 = 0.6839 kJ/kgK$
$h_f = h_3 = 69.5 kJ/kg$
$h_g = h_2 = 201.5 kJ/kg.$

At 30°C, $s_{f4} = s_{f1} = 0.0371 kJ/kg.K;$ $s_{g4} = s_{g1} = 0.7171 kJ/kg.K$
$h_{f4} = h_{f1} = 8.9 kJ/kg;$ $h_{g4} = hg1 = 174.2 kJ/kg$

Hence, dryness fractions at 1 and 4 are $s_1 = s_{f1} + x_1(s_{g1} - s_{f1})$

$$x_1 = \frac{s_1 - s_{f1}}{s_{g1} - s_{f1}} = \frac{0.6839 - 0.0371}{0.7171 - 0.0371} = 0.951$$

$$s_4 = s_{f4} + x_4(s_{g4} - s_{f4})$$

$$x_4 = \frac{s_4 - s_{f4}}{s_{g4} - s_{f4}} = \frac{0.2559 - 0.0371}{0.7171 - 0.0371} = 0.322$$

$$h_1 = h_{f1} + x_1(h_{g1} - h_{f1})$$
$$= 8.9 + 0.951\ (174.2 - 8.9) = 166\text{kJ/kg}$$
$$h_4 = h_{f4} + x_4(h_{g4} - h_{f4}) = 8.9 + 0.322\ (174.2 - 8.9) = 62.1\text{kJ/kg}$$

(i) Work of compression, Wcp = $h_2 - h_1$ = 201.5 – 166 = 35.5kJ/kg
(ii) Work of expansion, Wex = $h_3 - h_4$ = 69.5 – 62.1 = 7.4kJ/kg
(iii) Refrigerating effect, Qe = $h_1 - h_4$ = 166 – 62.1 = 103.9kJ/kg
(iv) Heat rejected, Qc = $h_2 - h_3$ = 201.5 – 69.5 = 132kJ/jg
(v) Net work W = Wep – Wex = 35.5 – 7.4 = 28.1kJ/kg
Or W = Qc – Qe = 132 – 103.9 = 28.1kJ/kg

$$COP_{ref} = \frac{Qe}{W} = \frac{103.9}{28.1} = 3.7$$

Also, we have for $COP_{ref\,(carnot)} = \frac{Te}{Tc - Te} = \frac{273 - 30}{35 - (-30)} = 3.74$

TONS OF REFRIGERATION

It was common practise to measure amounts of refrigeration in tons of refrigeration. One ton of refrigeration (abbreviation: TR) is the amount of cooling produced by one U.S. ton of ice in melting over a period of 24 hours. Since an American ton is 907.2 kg and the latent heat of fusion of water amounts to 334.9 kJ/kg, we

$$1TR = \frac{907.2 \times 334.9}{24 \times 3600} = 3.5165\text{kW}$$

If cooling required is X kW of refrigeration, the rate of refrigerant circulation necessary is given as

$$m' = \frac{\text{Useful refrigeration in kW}}{\text{Refrigerating effect in kJ/kg}} \quad \frac{Qe'}{Qe}$$

$$m' = \frac{X}{h_1 - h_4} \text{ Kg/s}$$

Where m' = mass flow rate of the refrigerant .

EXAMPLE

In the example 2.2, If the actual refrigerator operating on the same temperatures has a COP of 0.75 of the maximum, calculate the power consumption and heat rejected to the surroundings per ton of refrigeration.

SOLUTION

From the previous example
maximum COP = 3.74
Therefore
actual COP = 0.75 x 3.74 = 2.8

$Qe \quad = \quad 1$ ton of refrigeration $\quad = \quad 3.5165$ kW

(i) Power consumption per ton, $W' \quad = \quad \dfrac{Qe'}{COP_{Act}} \quad = \quad \dfrac{3.5165}{2.8}$

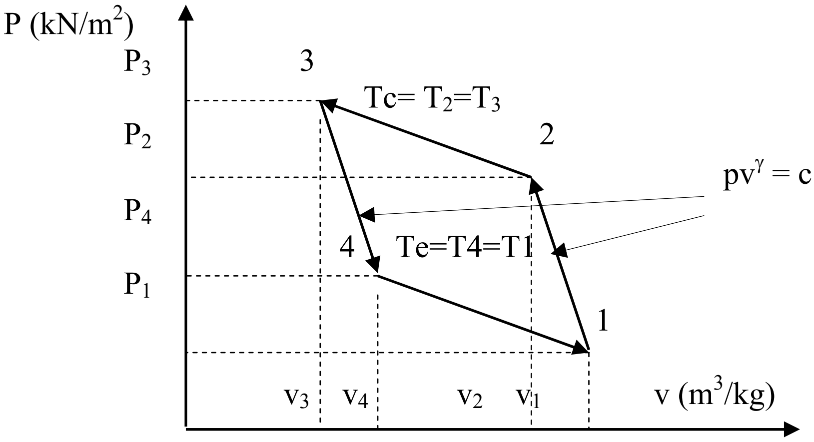
$$W' = 1.256\text{kW}$$

(i) Heat rejected per ton, $Qc' \quad = \quad Qe' \; + \; W'$

$$Qc' = 3.5165 + 1.256 = 4.7725 \text{ kW.}$$

GAS AS A REFRIGERANT IN REVERSED CARNOT CYCLE

Fig 2.4 shows the Carnot cycle with gas as a refrigerant, illustrated on p – v diagram.



Reversed Carnot Cycle with Gas as a Refrigerant on P- V Diagram.

The processes are as follows:

1-2 Isentropic compression; $\quad Q = O$
Pressure increases from $\quad P_1 = P_2$
Specific volume reduces from $\quad V_1$ to V_2
Temperature increases from $\quad Te = T_1$ to $Tc = T_2$

$$\text{Work done, } W_{1\text{-}2} = \frac{P_2V_2 - P_1V_1}{\gamma - 1} = \frac{R(Tc - Te)}{\gamma - 1}$$

2-3 Isothermal compression and heat rejection: $T_2 = T_3 = Tc$
Pressure increases from $\quad P_2$ to P_3
Specific volume reduces from V_2 to V_3
Work done, $\quad W_{2\text{-}3} = P_2V_2 \, \text{In}(V_2/V_3) = RTc\,(V_2/V_3)$
Heat rejected $Qc = Q_{2-3} = W_{2\text{-}3}$ (for a perfect gas)

3-4 Isentropic expansion : $\quad Q = O$
Pressure falls from $\quad P_3$ to P_4
Specific volume increases from V_3 to V_4
Temperature decreases from $\quad Tc = T_3$ to $Te = T_4$

$$P_3V_3 - P_4V_4 \qquad\qquad R(Tc - Te)$$

Work done, $W_{3\text{-}4}$ = $\frac{\quad = \quad}{\gamma - 1}$ $\frac{\qquad}{\gamma - 1}$

4-1 Isothermal expansion and heat absorption: $T_4 = T_1 = Te$
Pressure increases from P_4 to P_1
Specific volume reduces from V_4 to V_1
Work done, $W_{4\text{-}1} = P_4V_4 \ln(V_1/V_4)$
$= RTc\,(V_1/V_4)$
Refrigerating effect, $Qe = Q_{4-1}$
$= W_{4-1}$ (for a perfect gas)

ACTUAL REFRIGERATION SYSTEMS

For the purpose of comparison between the actual and Carnot values the following term is often used.

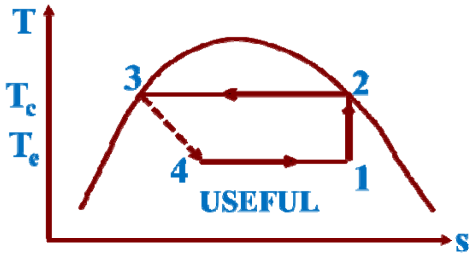
- **Relective Efficiency** $= \dfrac{COP_{ref}(actual)}{COP_{ref}(Carnot)}$

The reverse Carnot cycle with vapour as a refrigerant can be used as a practical cycle with modifications.

- The isothermal processes of heat rejection and absorption with condensation and evaporation respectively, are easily achievable in practice.
- But, the isentropic compression and expansion processes have certain limitation that required the following modifications:

REPLACEMENT OF THE EXPANSION DEVICE WITH THROTTLE VALVE

- Throttling process occur such that the initial enthalpy equals the final enthalpy.
- Refrigerating Effect, Q_e, is reduced by replacing the expansion device with a simple throttle valve.
- The Throttling process (3-4) is highly irreversible that the whole cycle becomes irreversible.



MODIFYING THE CONDITION AT INLET

(i) Wet Compression

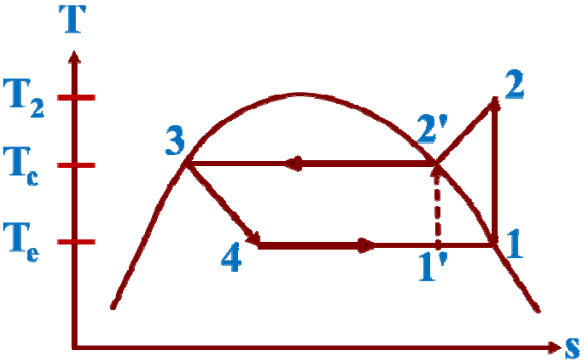
- Compression of wet-refrigerant (process 1'-2') in the Figure below, is called ***wet compression***.
- Wet-compression is not suitable in the reciprocating compressor due to the following reasons:

a. Liquid refrigerant may be trapped in the head of the cylinder and may damage the compressor valves and the cylinder itself.
b. Liquid-refrigerant droplets may wash away the lubricating oil from the walls of the cylinder.

(ii) Dry Compression

- It desirable to have compression with dry or superheated vapour refrigerant (process 1-2) as shown below, this is called ***dry compression***.
- With dry compression:

a) Discharge pressure P_2 = condensing pressure P_c
b) Discharge temperature T_2 > condensing temperature T_c or T_3.



QUESTION

The temperature in the evaporator of an ammonia refrigerator is -20°C and the temperature in the condenser is 32°C. Calculate the refrigerating effect per unit mass of refrigerant and the COP_{ref} for the following cycles:

a) the ideal reversed Carnot cycle
b) Dry saturated vapour delivered to the condenser after isentropic compression, the liquid leaves the condenser and is throttled to the evaporator pressure
c) Dry saturated vapour delivered to the compressor where it is compressed isentropically, the liquid leaves the condenser and is throttled to the evaporator pressure

3.0 ABSORPTION REFRIGERATION SYSTEM

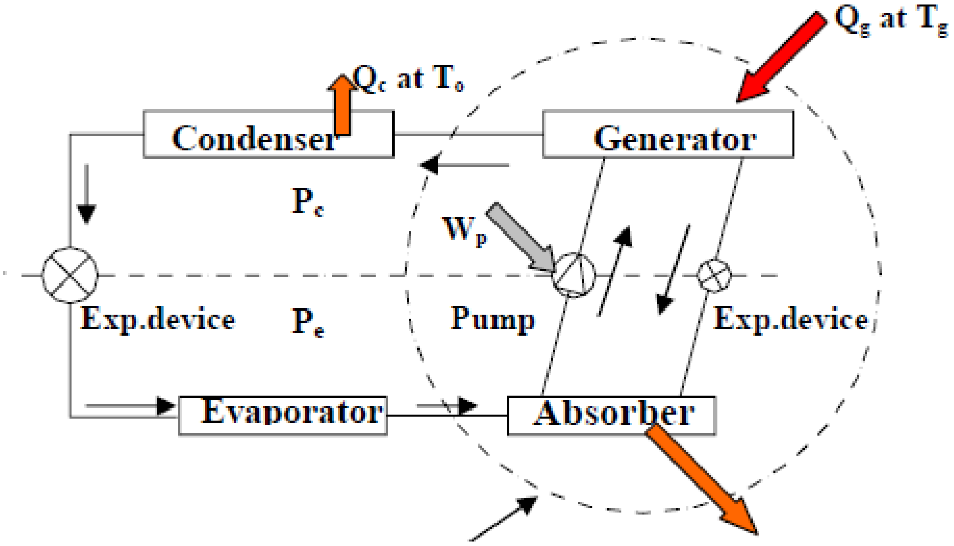
Similarity between vapour absorption and compression systems

- The absorption refrigeration cycle is similar to the compression cycle in that it employs volatile refrigerant, which alternatively vapourises under low pressure in the evaporator by absorbing latent heat from the material being cooled and condenses under high pressure in the condenser by surrending the latent heat to the condensing medium.

Differences between vapour absorption and compression systems

- The function of the compressor in vapour compression system is accomplished in three-step process in the vapour absorption system by the use of the absorber, pump and generator or reboiler as follows:

a) **Absorber**: Absoption of the refrigerant vapour by its weak or poor solution in a suitable absorbent, forming a strong or rich solution.
b) **Pump:** Pumping of the rich solution raising its pressure to the condenser pressure.
c) **Generator:** Distillation of the vapour from the rich solution leaving the poor solution for recycling.



Vapour Absorption Refrigeration System (VARS)

REFRIGERANT-ABSORBENT COMBINATIONS

There are different combinations use in different absorption refrigeration systems

- The systems that use solid absorbents are known as intermittent absorption Systems
- The systems that use liquid absorbents are known as continous absorption Systems
- Some of the combinations used in absorption refrigeration systems are listed below:

a) Ammonia as refrigerant and water as absorbent;
b) Water as refrigerant and litthium-bromide as absorbent;

- Sulphur dioxide as refrigerant and silical-gel as absorbent;
- Methylenechloride as refrigerant and dimethylethane as absorbent.

At present, there are two refrigerant-absorbent combinations that are in common use.

- The oldest in terms of usage is Ammonia as refrigerant and water as absorbent
- A more recent combination is water as refrigerant and litthium-bromide as absorbent

Criteria for selecting suitable refrigerant-absorbent combination

a) The absorbent must have a strong affinity for the refrigerant vapour.
b) The two fluids must be mutually soluble over the desired range of operating conditions.
c) The two fluids should be safe and stable both individually and in combination.
d) The absorbent should have a low volatility so that the refrigerant vapour leaving the generator will contain little or no absorbent
e) The working pressures in the system should be reasonably low and preferably near atmospheric pressure
f) The refrigerant should have a reasonably high latent heat value so that the required refrigerant flow rate is not excessive.

ADVANTAGES OF AMMONIA-WATER SYSTEMS

a) The water absorbent has a very strong affinity for ammonia vapour
b) The two fluids are mutually soluble over a wide range of operating conditions.
c) Both fluids are highly stable and are compatible with most materials found in refrigeration systems except copper and its alloys.
d) The ammonia refrigerant has a high latent heat value.

DISADVANTAGES OF AMMONIA-WATER SYSTEMS

a) Ammonia refrigerant is slightly toxic which limits its use in air-conditioning applications
b) In the presence of moisture, ammonia is corrosive to non-ferrous metals, such as copper and brass
c) Major Disadvantage: In the ammonia-water system, the major disadvantage is that absorbent (water) is reasonably volatile, so that the refrigerant (ammonia) vapour leaving the generator will usually contain appreciable amount of water vapour.

USE OF ANALYZER AND RECTIFIER IN AMMONIA WATER SYSTEM

- For the reason of volatility of the absorbent (water) the efficiency of the system can be improved by the use of analyzer and rectifier.

- **ANALYZER:** the analyzer is essentially a distillation column that is attached to the top of the generator. As the ammonia and water vapour coming off the generator rise up through the analyzer, they are cooled, and the water vapour, having the highest saturation temperature condenses and drains back to the generator, while the ammonia vapour continues to rise and leaves at the top of the analyzer.

- **RECTIFIER:** The ammonia vapour from the analyzer passes to the rectifier, or reflux condenser, where the remaining water vapour, and a small amount of ammonia vapour, condenses and drains back through the analyzer in the form of a weak reflux solution.

COEFFICIENT OF PERFORMANCE OF IDEAL ABSORPTION SYSTEM

- The COP absorption system is defined as the ratio of the refrigerating effect to the energy supplied to the generator

$$COP_{VARS} = \frac{Q_e}{Q_g + W_p} \approx \frac{Q_e}{Q_g}$$

THE THREE TEMPERATURE LEVELS IN VARS

- An ideal vapour absorption refrigeration system can be considered to be a combined system consisting of a Carnot heat engine and a Carnot refrigerator.
- Thus the COP of an ideal VARS increases as generator temperature (T_g) and evaporator temperature (T_e) increase and heat rejection temperature (T_o) decreases. However, the COP of actual VARS will be much less than that of an ideal VARS due to various internal and external irreversibilities present in actual systems.

4.0 REFRIGERANTS

- Refrigerants are the vital working fluid in a refrigeration system.
- They absorb heat from where it is not wanted and dispose it in another area.
- Due to several environmental issues such as ozone layer depletion and global warming and their relation to the various refrigerants used, the selection of suitable refrigerant has become one of the most important issues in recent times.

PRIMARY AND SECONDARY REFRIGERANTS

PRIMARY REFRIGERANTS:

- Primary refrigerants are those fluids, which are used directly as working fluids
- When used in compression or absorption systems, these fluids provide refrigeration by undergoing a phase change process in the evaporator.

SECONDARY REFRIGERANTS:

- As the name implies, secondary refrigerants are those liquids, which are used for transporting thermal energy from one location to other. Secondary refrigerants are also known under the name brines or antifreezes.

FUNCTION OF SECONDARY REFRIGERANT

- A secondary liquid coolant can be distributed long distances without problems. If a primary refrigerant were used, flashing might occur as a result of excessive pressure drop, creating operating and control problems.
- The secondary refrigerant also is useful when the primary refrigerant is toxic. For instance, an ammonia refrigerant plant can be installed in a remote location, with a safe secondary coolant distributed to the load.

BRINE

- Apart from water, solutions of water and another substance are often used as secondary refrigerant. These solutions are commonly referred to as “brines”. The origin of this name is that a solution of sodium chloride and water (the same constituents as seawater) was one of the first combinations used in ice making.

Types of Brine

- Sodium or calcium chloride and water
- Ethylene glycol and water
- Propylene glycol and water
- Methanol and water

PHYSICAL PROPERTIES OF BRINES

- Specific Heat: A high specific heat is desirable because a lower flow rate of brine is required to remove a given amount of heat. This reduces pumping power and perhaps equipment size.
- Thermal Conductivity: A high thermal conductivity increases the heat transfer rates.
- Viscosity: A low viscosity means there will be less friction and therefore a lower pumping power. Low viscosity also increases heat transfer rates
- Specific Gravity: A high specific gravity increases the heat transfer rate. However, a high specific gravity also increases pumping power.

REFRIGERANT SELECTION CRITERIA

Selection of refrigerant for a particular application is based on the following requirements:

i. **Thermodynamic and thermo-physical properties**
ii. **Environmental and safety properties, and**
iii. **Economics**

Thermodynamic and thermo-physical properties

The requirements are:

a) **Suction Pressure**: At a given evaporator temperature, the saturation pressure should be above atmospheric for prevention of air or moisture ingress into the system and ease of leak detection. Higher suction pressure is better as it leads to smaller compressor displacement
b) **Discharge pressure:** At a given condenser temperature, the discharge pressure should be as small as possible to allow light-weight construction of compressor, condenser etc.
c) **Pressure ratio:** Should be as small as possible for high volumetric efficiency and low power consumption
d) **Latent heat of vaporization:** Should be as large as possible so that the required mass flow rate per unit cooling capacity will be small
e) **Isentropic index of compression:** Should be as small as possible so that the temperature rise during compression will be small
f) **Liquid specific heat:** Should be small so that degree of sub-cooling will be large leading to smaller amount of flash gas at evaporator inlet
g) **Vapour specific heat:** Should be large so that the degree of superheating will be small
h) **Thermal conductivity:** Thermal conductivity in both liquid as well as vapour phase should be high for higher heat transfer coefficients
i) **Viscosity:** Viscosity should be small in both liquid and vapour phases for smaller frictional pressure drops.

The thermodynamic properties are interrelated and mainly depend on normal boiling point, critical temperature, molecular weight and structure.

- The normal boiling point indicates the useful temperature levels as it is directly related to the operating pressures.
- A high critical temperature yields higher COP due to smaller compressor superheat and smaller flash gas losses.
- On the other hand since the vapour pressure will be low when critical temperature is high, the volumetric capacity will be lower for refrigerants with high critical temperatures.
- This once again shows a need for trade-off between high COP and high volumetric capacity.

The important properties such as latent heat of vaporization and specific heat depend on the molecular weight and structure of the molecule.

- Trouton's rule shows that the latent heat of vaporization will be high for refrigerants having lower molecular weight.

- If specific heat of refrigerant vapour is low then the shape of the vapour dome will be such that the compression process starting with a saturated point terminates in the superheated zone (**i.e, compression process will be dry**).
- The freezing point of the refrigerant should be lower than the lowest operating temperature of the cycle to prevent blockage of refrigerant pipelines.

ENVIRONMENTAL AND SAFETY PROPERTIES:

At present the environment friendliness of the refrigerant is a major factor in deciding the usefulness of a particular refrigerant. The important environmental and safety properties are:

a) **Ozone Depletion Potential (ODP):** According to the Montreal protocol, the ODP of refrigerants should be zero, i.e., they should be non-ozone depleting substances.
   - Refrigerants having non-zero ODP have either already been phased-out (e.g. R 11, R 12) or will be phased-out in near-future(e.g. R22).
   - Since ODP depends mainly on the presence of chlorine or bromine in the molecules, refrigerants having either chlorine (i.e., CFCs and HCFCs) or bromine cannot be used under the new regulations

b) **Global Warming Potential (GWP):** Refrigerants should have as low a GWP value as possible to minimize the problem of global warming. Refrigerants with zero ODP but a high value of GWP (e.g. R134a) are likely to be regulated in future.

c) **Total Equivalent Warming Index (TEWI):** The factor TEWI considers both direct (due to release into atmosphere) and indirect (through energy consumption) contributions of refrigerants to global warming. Naturally, refrigerants with as a low a value of TEWI are preferable from global warming point of view.

d) **Toxicity:** Ideally, refrigerants used in a refrigeration system should be non-toxic.
   - However, all fluids other than air can be called as toxic as they will cause suffocation when their concentration is large enough.
   - Thus toxicity is a relative term, which becomes meaningful only when the degree of concentration and time of exposure required to produce harmful effects are specified.
   - Some fluids are toxic even in small concentrations.
   - Some fluids are mildly toxic, i.e., they are dangerous only when the concentration is large and duration of exposure is long.
   - Some refrigerants such as CFCs and HCFCs are non-toxic when mixed with air

In general the degree of hazard depends on:
- Amount of refrigerant used and total space
- Type of occupancy
- Presence of open flames
- Odour of refrigerant, and
- Maintenance condition

Thus from toxicity point-of-view, the usefulness of a particular refrigerant depends on the specific application.

e) **Flammability:** The refrigerants should preferably be non-flammable and non-explosive. For flammable refrigerants special precautions should be taken to avoid accidents.

f) **Chemical stability:** The refrigerants should be chemically stable as long as they are inside the refrigeration system.

g) **Compatibility** with common materials of construction (both metals and non-metals)

h) **Miscibility with lubricating oils:** Oil separators have to be used if the refrigerant is not miscible with lubricating oil.

i) **Dilelectric strength:** This is an important property for systems using hermetic compressors. For these systems the refrigerants should have as high a dielectric strength as possible.

j) **Ease of leak detection:** In the event of leakage of refrigerant from the system, it should be easy to detect the leaks.

ECONOMIC PROPERTIES

- The refrigerant used should preferably be inexpensive and easily available.

LEAK DETECTION

Vacuum Leak Test

Leaks may be detected either by pressurizing the system and checking for leakage to the outsides or by drawing a partial vacuum in the system and then checking for a rise in pressure on a test gauge.

- The vacuum method can indicate if there is a leak, but not where it is located.
- A vacuum leak test is normally performed after pressure testing and repair of leaks has been completed, as a final check.

Halide Torch

The halide torch is used for detecting halocarbon refrigerant leaks. This device consists of a small propane tank, a burner with a cooper element, and a sniffer hose. The hose is used with a probe at the joint where a leak is suspected to be. Any gas is drawn into the hose and to the burner. The burner's flame will change to a blue-green colour in the presence of both a halocarbon gas and cooper; indicating a leak. The halide torch has a leak sensitivity of about 1 ounce per year.

The Electronic Leak Detection

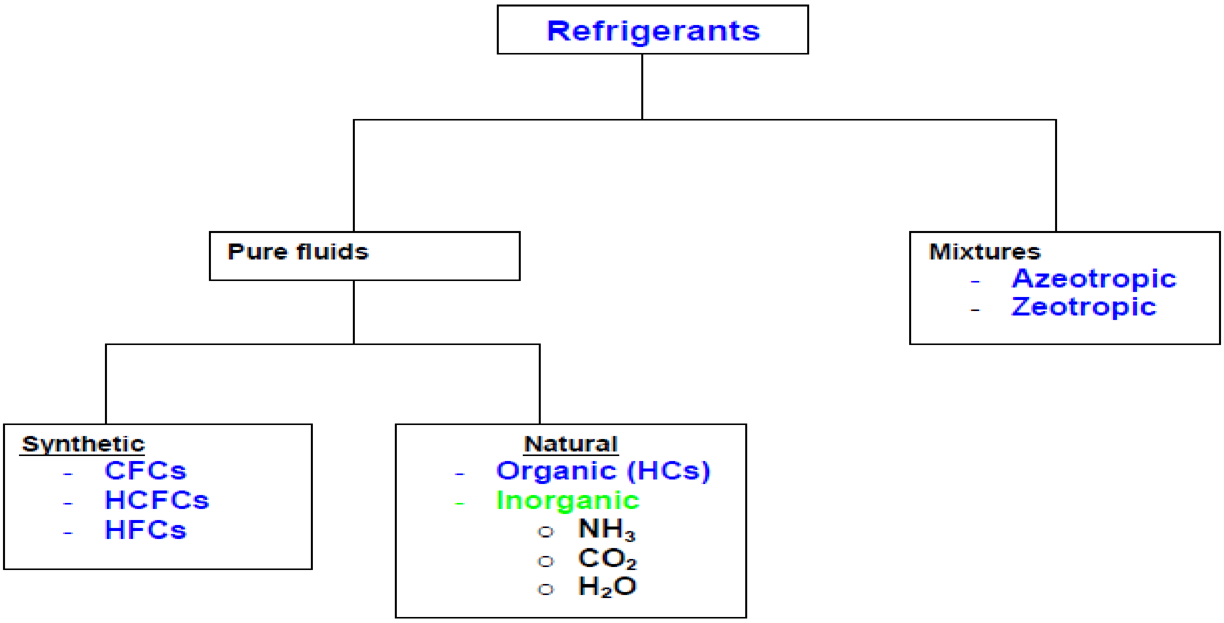
Electronic leak detection is a very sensitive devices that can detect extremely small leaks as little as 1 ounce per 100 years. The detector has an element in the probing tip that creates an electric emission in the presence of a halocarbon gas. The electric signal is converted in the device either to visual or an audible signal.

Soap Bubble Test

The soap bubble test is a simple yet often effective methods of discovering sources of leaks. The joint or connection is coated with a soap or detergent solution. Escaping gas forms bubbles at the leak. The soap bubble method can be used with any refrigerant. It is more effective when the pressure in the system is high.

DESIGNATION OF REFRIGERANTS

- The Figure below shows the classification of fluids used as refrigerants in vapour compression refrigeration systems.



REFRIGERANT NUMBERING SYSTEM

- A numbering system has been adopted to designate various refrigerants. From the number one can get some useful information about the type of refrigerant, its chemical composition, molecular weight etc.
- All the refrigerants are designated by R followed by a unique number

i) Fully Saturated, Halogenated Compounds

These refrigerants are derivatives of alkanes (C_nH_{2n+2}) such as methane (CH_4), ethane (C_2H_6). These refrigerants are designated by **R XYZ**, where:

- X+1 indicates the number of Carbon (C) atoms
- Y-1 indicates number of Hydrogen (H) atoms, and
- Z indicates number of Fluorine (F) atoms
- The balance indicates number of Chlorine atoms.
- Only 2 digits indicates that the value of X is zero.

QUESTION

Determine the chemical formula and name of the following refrigerants:

(i) R12,
(ii) R22,
(iii) R32,
(iv) R134a
(v) R152a

Letter a stands for isomer, e.g. molecules having same chemical composition but different atomic arrangement, e.g. R134 and R134a.

ii) Inorganic Refrigerants: These are designated by number 7 followed by the molecular weight of the refrigerant (rounded-off).

- Ex.: Ammonia: Molecular weight is 17, ∴ the designation is R717
- Carbon dioxide: Molecular weight is 44, ∴ the designation is R744
- Water: Molecular weight is 18, ∴ the designation is R718

iii) Mixtures: Azeotropic mixtures are designated by 500 series, where as zeotropic refrigerants (e.g. non-azeotropic mixtures) are designated by 400 series.

Azeotropic Mixtures:

- R500: Mixture of R12 (73.8 %) and R152a (26.2%)
- R502: Mixture of R22 (48.8 %) and R115 (51.2%)
- R503: Mixture of R23 (40.1 %) and R13 (59.9%)
- R507A: Mixture of R125 (50%) and R143a (50%)

Zeotropic Mixtures:

- R404A : Mixture of R125 (44%), R143a (52%) and R134a (4%)
- R407A : Mixture of R32 (20%), R125 (40%) and R134a (40%)
- R407B : Mixture of R32 (10%), R125 (70%) and R134a (20%)
- R410A : Mixture of R32 (50%) and R125 (50%)

iv) Hydrocarbons:

- Propane (C_3H_8) : R290
- n-butane (C_4H_{10}) : R600
- Iso-butane (C_4H_{10}) : R600a
- Unsaturated Hydrocarbons: R1150 (C_2H_4)
  R1270 (C_3H_6)

CHLOROFLUOROCARBON (CFC) REFRIGERANTS AND THE ENVIRONMENTAL PROBLEMS

- Prior to the environmental issues of ozone layer depletion and global warming, the most widely used refrigerants were CFCs (R11, R12, R22, R502) and ammonia.
- Of these, R11 was primarily used with centrifugal compressors in air conditioning applications;
- R12 was used primarily in small capacity refrigeration and cold storage applications; and
- Other refrigerants were used in large systems such as large air conditioning plants or cold storages.

OZONE LAYER DEPLETION

- The depletion of stratospheric ozone layer was attributed to chlorine and bromine containing chemicals such as Halons, CFCs, HCFCs etc.
- Since ozone layer depletion could lead to catastrophe on a global level, it has been agreed by the global community to phase out the ozone depleting substances (ODS).
- As a result except ammonia, all the other refrigerants used in cold storages had to be phased-out and a search for suitable replacements began in earnest.

GLOBAL WARMING

- It was also observed that in addition to ozone layer depletion, most of the conventional synthetic refrigerants also cause significant global warming.
- In view of the environmental problems caused by the synthetic refrigerants, opinions differed on replacements for conventional refrigerants.

The alternate refrigerants can be classified into two broad groups:

a) Non-ODS, synthetic refrigerants based on Hydro-Fluoro-Carbons (HFCs) and their blends
b) Natural refrigerants including ammonia, carbon dioxide, hydrocarbons and their blends

HYDRO-FLUOROCARBONS (HFCS) AND THEIR BLENDS

- HFCs and their blends are synthetic refrigerants and are normally non-toxic and non-flammable.
- It is also possible to use blends of various HFCs to obtain new refrigerant mixtures with required properties to suit specific applications.
- However, most of these blends are non-azeotropic in nature, as a result there could be significant temperature glides during evaporation and condensation, and it is also important take precautions to prevent leakage, as this will change the composition of the mixture.

NATURAL REFRIGERANTS

- It should be noted that the use of natural refrigerants such as carbon dioxide, hydrocarbons and ammonia are not new refrigerants, but this is a revival of the once-used-and-discarded technologies in a much better form.

Advantages of Natural Refrigerants

- They are familiar in terms of their strengths and weaknesses.
- They are completely environment friendly, unlike the HFC based refrigerants, which do have considerable global warming potential.

5.0 PRINCIPLES AND APPLICATIONS OF AIR-CONDITIONING

Air-conditioning is the process of treating air of a confined space to control simultaneously its temperature, humidity, cleanliness, and distribution to meet the comfort requirements of the occupants (human beings or animals) or for the proper performance of some industrial or scientific process.

Full air-conditioning implies that the purity, movement, temperature and relative humidity of the air be controlled within the limits imposed by design specifications.

COMFORT CONDITIONING

Comfort: Comfort can be defined as the state of mind that expresses satisfaction with the thermal environment. It has been established that it is a subjective terms; what is comfort to a person may not be for another.

Reasons why Air-conditioning is necessary

a) Heat gains from sunlight and electric lighting, in particular, may cause unpleasantly high temperatures in rooms, unless windows are opened.
b) If windows are opened, then wind speeds will cause excessive draughts.
c) The inner areas of deep buildings will not really benefit at all from opened windows.
d) Also, if windows are opened, noise and dirt enter and are objectionable, becoming worse on the lower floors of buildings, particularly in urban and industrial areas.

VENTILATION

- Lack of adequate ventilation means a great discomfort for the occupants
- Ventilation will provides a controlled and uniform means of air distribution in place of the unsatisfactory results obtained with opened windows.
- Mechanical ventilation without refrigeration is only a partial solution.

INDUSTRIAL AIR-CONDITIONING

The term industrial air-conditioning refers to the provision of at least a partial measure of comfort for workers in hostile environment but also to control air conditions so that they are favourable to preservation and proper functioning of some objects and material.

- **Sport Heating:** During cold weather it may be more practical to warm a confined space where a worker is located. Example is the use of an infrared heater; when its surfaces are heated to a high temperature by means of burner or by electricity, they radiate heat to the affected areas.

- **Spot Cooling:** It may be impractical to cool an entire mill, but conditions may be kept tolerable for workers by directing a stream of cool air on to occupied areas.

- **Environmental Laboratories:** The role of air conditioning varies from one environmental laboratory to another. In one a temperature of -40^oC must be maintained to test engines at low temperatures, and in another a high temperature and humidity may be maintained to study the behaviour of animal in tropical climates.

- **Photographic Products:** The photographic products industry is a large user of air-conditioning and refrigeration. Raw photographic material deteriorates rapidly in high temperatures and humidity, and other materials used in coating film require careful control of temperature.

- **Precision Parts and Clean Room:** For manufacturing of precision metal parts air-conditioning performs three services keeping the temperatures uniform so that the metal will not expand and contract, maintaining a humidity so that rust is prevented, and filtering the air to minimize dust.

- **Computer Room:** The air-conditioning system for computer rooms should control the temperature, humidity, and cleanness of the air. Some electronic components operate in a faulty manner if they become too hot, and one means of preventing such localized high temperature is in the range of 20 to 23^oC. The electronic components in the computer function favourably at even lower temperatures, but this temperature is a compromise with the lowest comfortable temperature for occupants.

UNITARY AIR-CONDITIONING

Air-conditioning units are available as unitary of self-contained (single package) units.

Advantages

- The fact that they are mass-produced and factory-assembled usually means lower production and installation costs.
- With proper selection and control they may also provide relatively low operating costs.

Disadvantages

- There are relatively few options with respect to sizing the evaporator, condenser, fans, compressor and controls.
- Since each unit must be capable of meeting the peak load of the space it serves; the installed capacity and connected electrical load are usually larger than with a central system.

EXAMPLES OF UNITARY AIR-CONDITIONING

a) **Rooftop Units:** Rooftop units are primarily applied in low-rise buildings with flat roofs, such as stores, shopping centres, and factories. For better air distribution in the conditioned space the conditioned air should be ducted from the rooftop unit to multiple outlets instead of introducing the total airflow rate at one position.

b) **Window Units:** They are available in capacities from ½ to 2½ tons and are used to cool small spaces. They are primarily found in residential applications and small offices. They have no ducted air distribution. Window units are designed for minimal installation cost. Such units can be moved easily from one location to another. The appearance and noise of these units limits their application.

c) **Split-System Air-Conditioning Units:** In this arrangement, the unit is split into two; the blower-coil units (evaporating units) and the condensing unit. The blower-coil unit is installed inside the conditioned space and it consists of fan, evaporating coil and controls. The condensing unit is installed outdoor. It consists of a compressor and condenser.

CONDENSING UNIT

It consists of a compressor and condenser, and it performs the function of drawing low-pressure vapour from the evaporator, compressing and condensing the refrigerant, and supplying it at high pressure to the expansion device. Condensing units are installed outdoor to serve an evaporator located inside the building

Psychrometric deals with the determination of the thermodynamic properties of moist air and the utilization of these properties in the analysis of conditions and processes involving moist air.

- **Psychrometry** is the study of the properties of mixtures of air and water vapour. the properties of moist air are called Psychrometric properties.
- Atmospheric air is a mixture of many gases plus water vapour and a number of pollutants. The amount of water vapour and pollutants vary from place to place. The mixture of air and water vapour is known as ***moist air***.

COMPOSITION OF STANDARD AIR

- The moist air can be thought of as a mixture of dry air and moisture. For all practical purposes, the composition of dry air can be considered as constant.

Constituent	Molecular weight	Mol fraction
Oxygen	32.000	0.2095
Nitrogen	28.016	0.7809
Argon	39.944	0.0093
Carbon dioxide	44.010	0.0003

- Based on the above composition the *molecular weight of dry air is found to be* **28.966** *and the gas constant R is* **287.035 J/kg.K.**

MOIST AIR

- As mentioned before the air to be processed in air conditioning systems is a mixture of dry air and water vapour. While the composition of dry air is constant, the amount of water vapour present in the air may vary from zero to a maximum depending upon the temperature and pressure of the mixture (dry air + water vapour).
- For calculation purposes, the molecular weight of water vapour is taken as **18.015** and its gas constant is **461.52 J/kg.K**.

SATURATED AIR

- At a given temperature and pressure the dry air can only hold a certain maximum amount of moisture. When the moisture content is maximum, then the air is known as *saturated air*.

Basic gas laws for moist air:

According to the ***Gibbs-Dalton law*** for a mixture of perfect gases, the total pressure exerted by the mixture is equal to the sum of partial pressures of the constituent gases. According to this law, for a homogeneous perfect gas mixture occupying a volume V and at temperature T, each constituent gas behaves as though the other gases are not present (i.e., there is no interaction between the gases). Each gas obeys perfect gas equation. Hence, the partial pressures exerted by each gas, p_1, p_2, p_3 … and the total pressure p_t are given by:

$$p_1 = \frac{n_1 R_u T}{V};\ p_2 = \frac{n_2 R_u T}{V};\ p_3 = \frac{n_3 R_u T}{V}$$

$$p_t = p_1 + p_2 + p_3 + \ldots\ldots$$

where n_1, n_2, n_3, … are the number of moles of gases 1, 2, 3, …

Applying this equation to moist air.

$$p = p_t = p_a + p_v$$

where $p = p_t$ = total barometric pressure
p_a = partial pressure of dry air
p_v = partial pressure of water vapour

IMPORTANT PSYCHROMETRIC PROPERTIES:

Dry Bulb Temperature (DBT) is the temperature of the moist air as measured by a standard thermometer or other temperature measuring instruments.

Saturated Vapour Pressure (p_{sat}) is the saturated partial pressure of water vapour at the dry bulb temperature.

Relative Humidity (Φ) is defined as the ratio of the mole fraction of water vapour in moist air to mole fraction of water vapour in saturated air at the same temperature and pressure. Using perfect gas equation we can show that:

$$\phi = \frac{\text{partial pressure of water vapour}}{\text{saturation pressure of pure water vapour at same temperature}} = \frac{p_v}{p_{sat}}$$

Relative humidity is normally expressed as a percentage. When Φ is 100 percent, the air is saturated.

Humidity Ratio (W): The humidity ratio (or specific humidity) W is the mass of water associated with each kilogram of dry air. Assuming both water vapour and dry air to be perfect gases, the humidity ratio is given by:

$$W = \frac{\text{kg of water vapour}}{\text{kg of dry air}} = \frac{p_v V / R_v T}{p_a V / R_a T} = \frac{p_v / R_v}{(p_t - p_v)/R_a}$$

Substituting the values of gas constants of water vapour and air R_v and R_a in the above equation; the humidity ratio is given by:

$$W = 0.622 \frac{p_v}{p_t - p_v}$$

For a given barometric pressure p_t, given the DBT, we can find the saturated vapour pressure p_{sat} from the thermodynamic property tables on steam. Using the above equation, we can find the humidity ratio at saturated conditions, W_{sat}.

Dew-Point Temperature: If unsaturated moist air is cooled at constant pressure, then the temperature at which the moisture in the air begins to condense is known as ***dew-point temperature (DPT)*** of air. An approximate equation for dew-point temperature is given by:

$$DPT = \frac{4030(DBT + 235)}{4030 - (DBT + 235)\ln\phi} - 235$$

Degree of Saturation μ: The degree of saturation is the ratio of the humidity ratio W to the humidity ratio of a saturated mixture W_s at the same temperature and pressure, i.e.,

$$\mu = \left| \frac{W}{W_s} \right|_{t,P}$$

Enthalpy: The enthalpy of moist air is the sum of the enthalpy of the dry air and the enthalpy of the water vapour. Enthalpy values are always based on some reference value. For moist air, the enthalpy of dry air is given a zero value at 0°C, and for water vapour the enthalpy of saturated water is taken as zero at 0°C.

The enthalpy of moist air is given by:

$$h = h_a + Wh_g = c_p t + W(h_{fg} + c_{pw} t)$$

Where c_p = specific heat of dry air at constant pressure, kJ/kg.K
c_{pw} = specific heat of water vapour, kJ/kg.K
t = Dry-bulb temperature of air-vapour mixture, ^oC
W = Humidity ratio, kg of water vapour/kg of dry air
h_a = enthalpy of dry air at temperature t, kJ/kg
h_g = enthalpy of water vapour at temp t, kJ/kg
h_{fg} = latent heat of vaporization at 0^oC, kJ/kg

The unit of h is kJ/kg of dry air. Substituting the approximate values of c_p and h_g, we obtain:

$$h = 1.005\,t + W(2501 + 1.88t)$$

Humid specific heat: From the equation for enthalpy of moist air, the humid specific heat of moist air can be written as:

$$c_{pm} = c_p + W.c_{pw}$$

where c_{pm} = humid specific heat, kJ/kg.K
c_p = specific heat of dry air, kJ/kg.K
c_{pw} = specific heat of water vapour, kJ/kg
W = humidity ratio, kg of water vapour/kg of dry air

Since the second term in the above equation (w.c_{pw}) is very small compared to the first term, for all practical purposes, the humid specific heat of moist air, c_{pm} can be taken as 1.0216 kJ/kg dry air.K

Specific Volume: The specific volume is defined as the number of cubic meters of moist air per kilogram of dry air. From perfect gas equation since the volumes occupied by the individual substances are the same, the specific volume is also equal to the number of cubic meters of dry air per kilogram of dry air, i.e.,

$$v = \frac{R_a T}{p_a} = \frac{R_a T}{p_t - p_v} \qquad m^3/\text{kg dry air}$$

Psychrometric chart: A *Psychrometric chart* graphically represents the thermodynamic properties of moist air.

Standard psychrometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapour pressure or humidity ratio (ordinate). The Left Hand Side of the psychrometric chart is bounded by the saturation line.

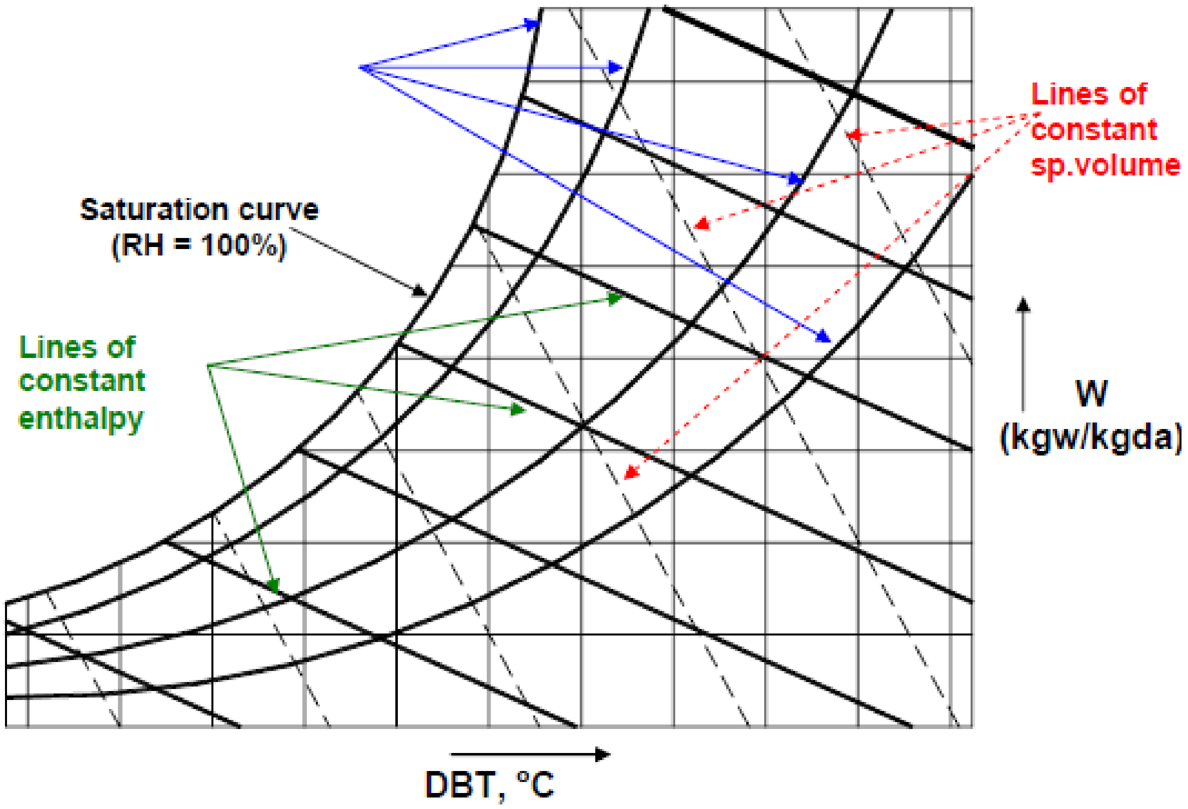
Adiabatic Saturation Temperature: is defined as that temperature at which water, by evaporating into air, can bring the air to saturation at the same temperature adiabatically.

Adiabatic Saturator: An adiabatic saturator is a device using which one can measure theoretically the adiabatic saturation temperature of air.

Schematic of a psychrometric chart for a given barometric pressure

Thermodynamic Wet Bulb Temperature:
After the adiabatic saturator has achieved a steady-state condition, the temperature indicated by the thermometer immersed in the water is the *thermodynamic wet-bulb temperature*.

PSYCHROMETER:
Any instrument capable of measuring the psychrometric state of air is called a psychrometer. Two types of psychrometers are commonly used. Each comprises of two thermometers with the bulb of one covered by a moist wick. The two sensing bulbs are separated and shaded from each other so that the radiation heat transfer between them becomes negligible.



The sling psychrometer: is widely used for measurements involving room air or other applications where the air velocity inside the room is small. The sling psychrometer consists of two thermometers mounted side by side and fitted in a frame with a handle for whirling the device through air. The required air circulation (≈ 3 to 5 m/s) over the sensing bulbs is obtained by whirling the psychrometer (≈ 300 RPM). Readings are taken when both the thermometers show steady-state readings.

Aspirated Psychrometer: In the *aspirated psychrometer*, the thermometers remain stationary, and a small fan, blower or syringe moves the air across the thermometer bulbs.
Other types of psychrometric instruments:

(a) Dunmore Electric Hygrometer,
(b) DPT meter,
(c) Hygrometer (Using horse's or human hair)

CALCULATION OF PSYCHROMETRIC PROPERTIES

i) Modified Apjohn equation:

$$p_v = p_v' - \frac{1.8p(t-t')}{2700}$$

ii) Modified Ferrel equation:

$$p_v = p_v' - 0.00066p(t-t')\left[1+\frac{1.8t}{1571}\right]$$

iii) Carrier equation:

$$p_v = p_v' - \frac{1.8(p-p_v')(t-t')}{2800-1.3(1.8t+32)}$$

where t = dry bulb temperature, °C
t' = wet bulb temperature, °C
p = barometric pressure
p_v = vapour pressure
p_v' = saturation vapour pressure at wet-bulb temperature

QUESTION

Moist air at 1 atm. pressure has a dry bulb temperature of 32°C and a wet bulb temperature of 26°C. Calculate:

(a) the partial pressure of water vapour,
(b) humidity ratio,
(c) relative humidity,
(d) dew point temperature,
(e) density of dry air in the mixture,
(f) density of water vapour in the mixture and
(g) enthalpy of moist air using perfect gas law model and psychrometric equations.

Solution:

(a) Using modified Apjohn equation and the values of DBT, WBT and barometric pressure, the vapour pressure is found to be:

p_v = **2.956 kPa (Ans.)**

(b) The humidity ratio W is given by:

W = 0.622 x 2.956/(101.325-2.956)
= **0.0187 kgw/kgda (Ans.)**

(c) Relative humidity RH is given by:

RH = (p_v/p_s) x 100

= $(p_v/\text{saturation pressure at } 32^{o}C) \times 100$

From steam tables, the saturation pressure of water at 32°C is 4.7552 kPa, hence,

RH = $(2.956/4.7552) \times 100$
= **62.16% (Ans.)**

(d) Dew point temperature is the saturation temperature of steam at 2.956 kPa. Hence using steam tables we find that:

DPT = $T_{sat}(2.956 \text{ kPa})$
= **23.8°C (Ans.)**

(e) Density of dry air and water vapour
Applying perfect gas law to dry air:

Density of dry air
ρ_a = (p_a/R_aT)
= $(p_t - p_v)/R_aT$
= $(101.325-2.956)/(287.035 \times 305) \times 10^3$
= **1.1236 kg/m³ of dry air (Ans.)**

(f) Similarly the density of water vapour in air is obtained using perfect gas law as:
Density of water vapour
ρv = (p_v/R_vT)
= $2.956 \times 10^3/(461.52 \times 305)$
= **0.021 kg/m³**

(g) Enthalpy of moist air is found from the equation:
h = $1.005 \times t + W(2501+1.88 \times t)$
= $1.005 \times 32 + 0.0187(2501+1.88 \times 32)$
h = **80.05 kJ/kg of dry air (Ans.)**