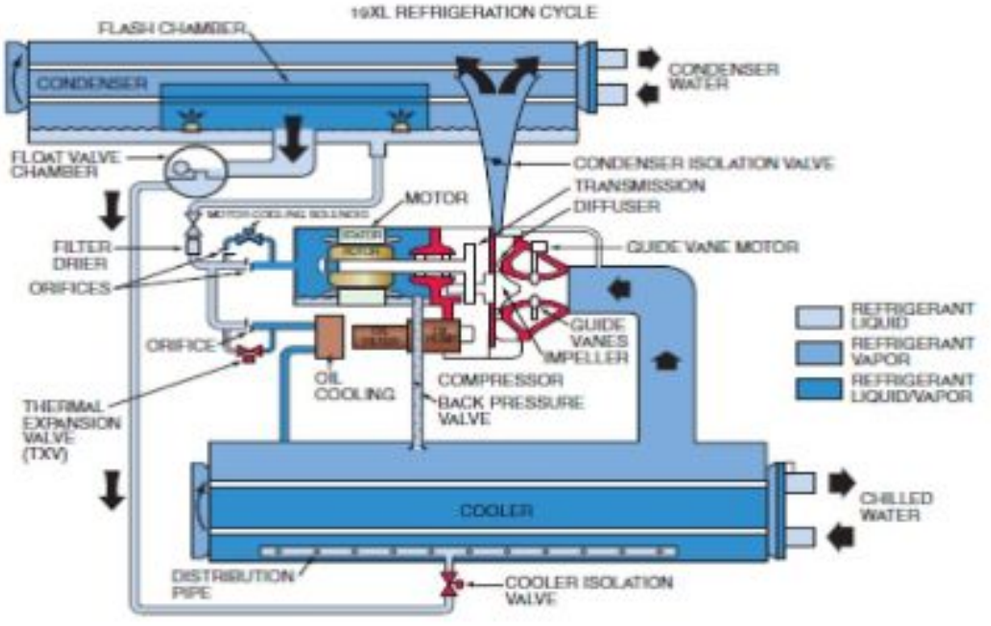
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مبادئ تكييف الهواء

المرحلة الاولى

Principles of Air Conditioning



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Unit 1

Principles of thermodynamics

Property :

A property of a system is any characteristic of a system which can be measured directly or indirectly while system remains at state of equilibrium. The properties of a fluid may be classified as follow:

Fundamental properties or measurable properties defining the physical condition of the fluid are: Pressure, Specific volume, Temperature.

Thermodynamic properties defining the thermal and energy conditions of the fluid are: Internal energy, Flow work, Enthalpy, Entropy.

The thermodynamic properties of the fluid cannot be measured directly but they are calculated with the help of fundamental properties.

State :

A state of a system is a condition of a system at any particular moment which can be identified by the properties of a system. The condition of a system is specified by the values of its properties. Since there are numerous relationships among the properties of particular system, the values of few properties will often identify state completely because all other properties can be determined in terms of these few. Precisely how many properties are required to specify the state of a system depends on the complexity of the system.

Temperature :

Temperature measures the heat intensity or heat level of a substance. Temperature alone does not give the amount of heat in a substance. It indicates the degree of warmth, or how **hot** or **cold** the substance or body is.

In the molecular theory of heat, temperature indicates the speed of motion of the molecules.



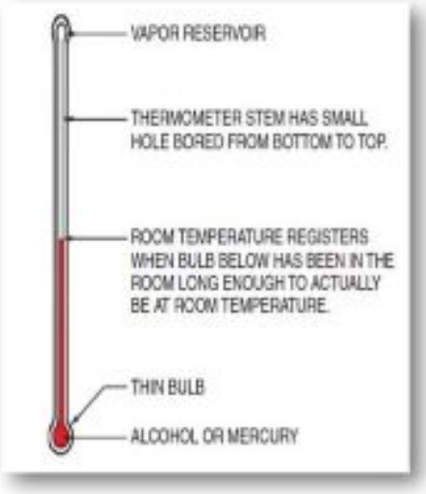
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Thermometers :

Temperature is measured with a thermometer. This is usually through uniform expansion of a liquid in a sealed glass tube. There is a bulb at the bottom of the tube and a quantity of mercury or alcohol inside. The liquid will rise and fall in the tube as the temperature changes. The tube is calibrated or marked off in degrees using the desired temperature scale.

There are numerous other thermometers that are popular and easy to use like dial-stem thermometer, analog and digital thermometers, electrical thermometers

(thermocouple, thermistor) and infrared thermometer.

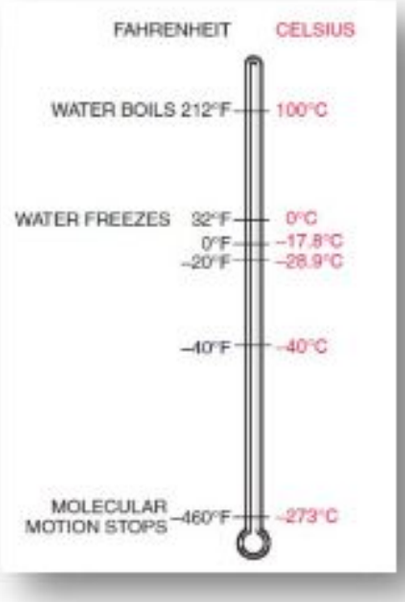




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Temperature :

The freezing point of water is 0 degrees Celsius (**0 °C**) (32 degrees Fahrenheit) (**32°F**), and that the boiling point is 100 degrees Celsius (100 °C), (212 degrees Fahrenheit) (212°F). These points are commonly indicated on a thermometer, which is an instrument that measures temperature. We must qualify the statement that water boils at 100 °C. Pure water boils at 100 °C when standard atmospheric conditions exist. Standard conditions are sea level with the barometer reading 101.325 kPa (14.696 psia). This qualification concerns the relationship of the earth's atmosphere to the boiling point.



Temperature conversion :

Formula:

$$\text{Temperature in °F} = \left(\frac{180}{100} \times \text{Temperature °C}\right) + 32$$

or

$$\text{Temperature in °F} = \left(\frac{9}{5} \times \text{°C}\right) + 32$$

Formula:

$$\text{Temperature in °C} = \frac{100}{180} \times (\text{Temperature °F} - 32)$$

or

$$\text{Temperature in °C} = \frac{5}{9} \times (\text{°F} - 32)$$

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Absolute Temperature Scales (Kelvin and Rankine) :

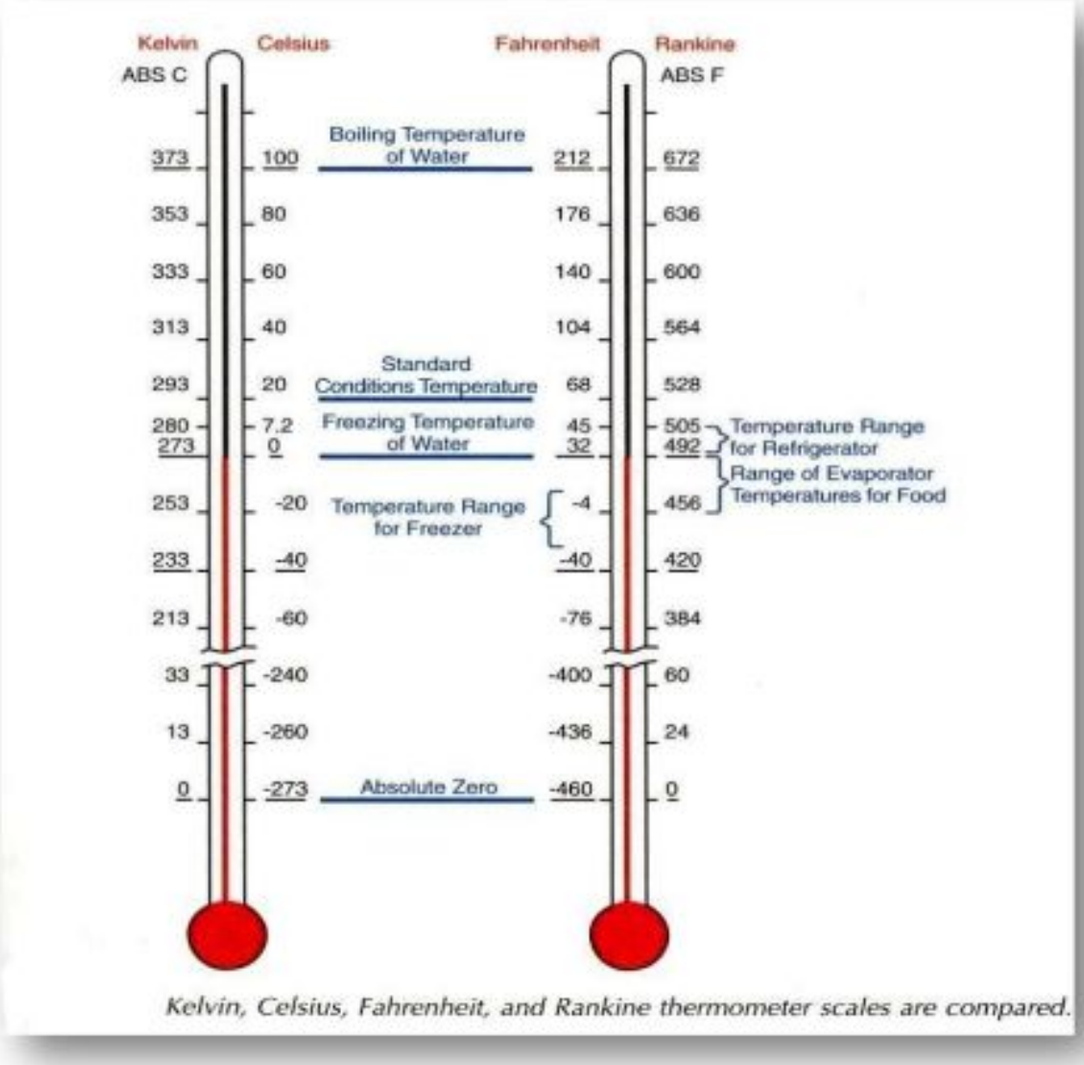
Absolute zero is that temperature where molecular motion stops. It is the lowest temperature possible. There is no more heat in the substance at this point.

Two absolute temperature scale are used in **cryogenics** (**very low temperature work**).These two scales are the **Kelvin (K)** (Celsius Absolute) scale and the **Rankine (°R)** (Fahrenheit Absolute) scale.

$$K = °C + 273$$

$$°R = °F + 460$$

$$K = 5/9\ °R$$



Kelvin, Celsius, Fahrenheit, and Rankine thermometer scales are compared.

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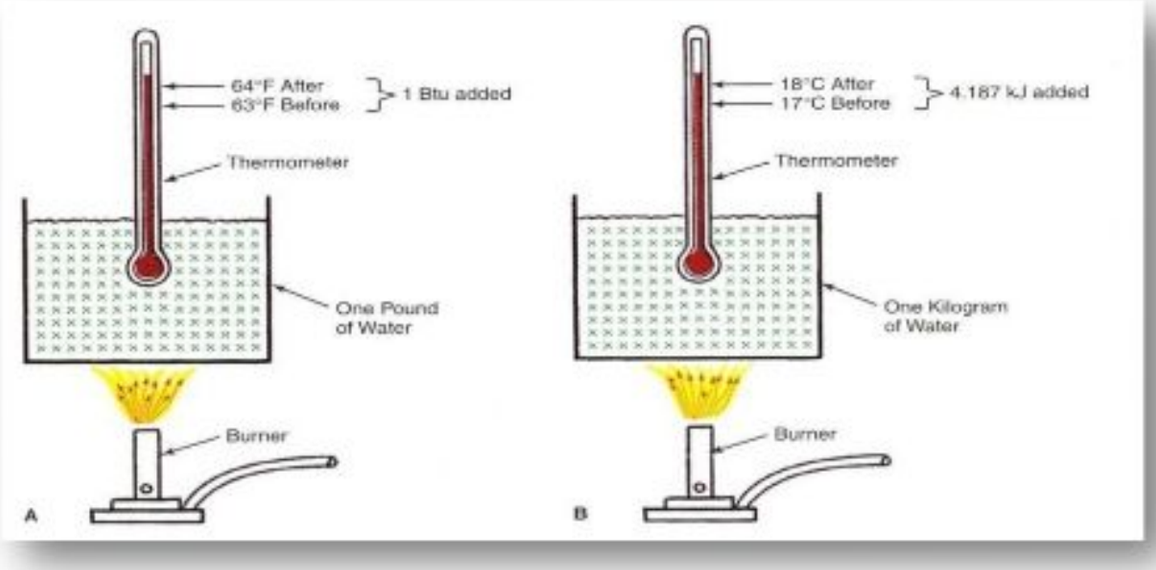
Heat :

Heat is a form of energy. It has a relationship to the atom. All substances are made up of tiny atoms, which combine to make molecules. All the atoms are in a state of rapid motion. As the temperature of a substance increases, the atoms move more rapidly. As the temperature drops, they slow down. If all heat is removed from a substance (absolute zero) all molecular motion stops.

The amount of heat in a substance may greatly affect the nature of the substance, adding heat causes most substances to expand, removing heat causes them to contract.

Most substance change their physical state with the addition or removal of heat.

The unit of heat is the Kilojoule (kJ) or British thermal unit (Btu). The amount of heat required to raise the temperature of 1 kg of water 1 °C is equal to 4.187 KJ. In British unit, the amount of heat required to raise the temperature of 1 pound of water 1 °F is equal to 1 Btu.



Specific Heat :

The specific heat of a substance is the amount of heat that must be added or released to change the temperature of one kilogram of the substance one degree Kelvin (K).

$Q = M \times sp.ht. \times \triangle T$

Where:

Q = Heat added or removed (kJ)

M = Mass (kg)

sp.ht.= Specific heat (kJ/kgK)

$\triangle T$ = Temperature difference (K)

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The approximate specific heats of several important substances are:

C_P = 1.0 kJ/kg.K dry air

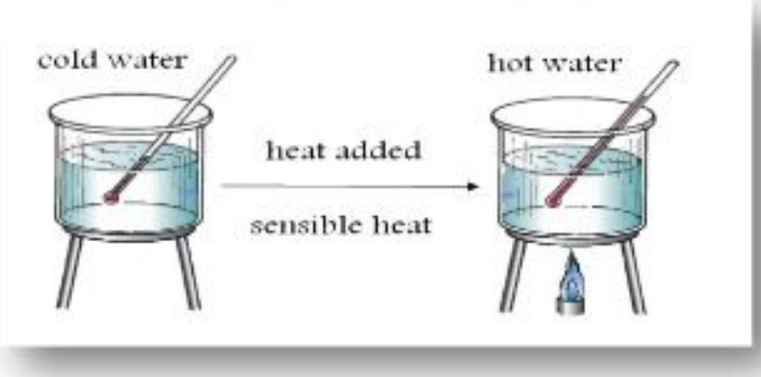
C_P = 4.19 kJ/kg.K liquid water

C_P = 1.88 kJ/kg.K water vapour

Material	Specific Heat Capacity	
	Btu/lb./F	kJ/kg·K
Wood	0.327	1.369
Water	1.0	4.187
Ice	0.504	2.110
Iron	0.129	0.540
Mercury	0.0333	0.139
Alcohol	0.615	2.575
Copper	0.095	0.398
Sulphur	0.177	0.741
Glass	0.187	0.783
Graphite	0.200	0.837
Brick	0.200	0.837
Glycerine	0.576	2.412
R-717 (Liquid ammonia at 40 °F)	1.1	4.606
R-744 (Carbon dioxide at 40 °F)	0.6	2.512
R-502	0.255	1.068
Salt Brine 20%	0.85	3.559
R-12	0.213	0.892
R-22	0.26	1.089
The above values may be used for computations which involve no "change of state." If a change of state is involved, the specific heat for each state of the substance must be used.		

Sensible Heat :

Heat which causes a change in temperature in a substance is called sensible heat. When a substance is heated (heat added) and the temperature rises as the heat is added, the increase in heat is called sensible heat. Likewise, heat may be removed from a substance (heat subtracted). If the temperature falls, the heat removed is, again, sensible heat.

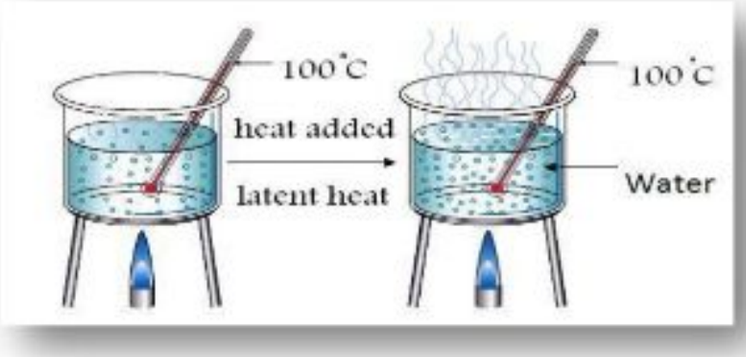


Latent Heat :

Heat which brings about a change of state with no change in temperature is called latent (hidden) heat.

All pure substances are able to change their state. Solids become liquids, liquids become gas. These changes of state occur at the same temperature and pressure combinations for any given substance. It takes the addition of heat or the removal of heat to produce these changes

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Latent Heat of Fusion :

A change of state for a substance from a solid to a liquid, or from a liquid to a solid involves the latent heat of fusion. It might also be termed the latent heat of melting, or the latent heat of freezing.

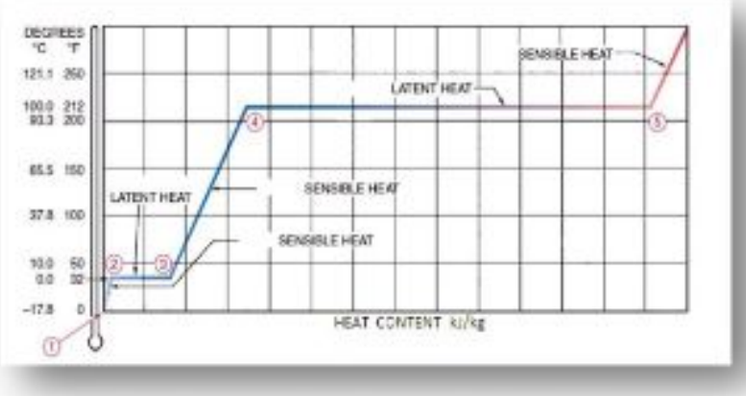
When one kg (pound) of ice melts, it absorbs 335kJ (144 BTU) at a constant temperature of 0 °C (32°F). If one kg (pound) of water is to be frozen into ice, 335 kJ (144 BTU) must be removed from the water at a constant temperature of 0 °C (32°F).

Latent Heat of Evaporation :

A change of a substance from a liquid to a vapour, or from a vapour back to a liquid involves the latent heat of evaporation. Since boiling is only a rapid evaporating process, it might also be called the latent heat of boiling, the latent heat of vaporization, or for the reverse process, the latent heat of condensation. When one kg or (pound) of water boils or evaporates, it absorbs 2257 kJ (970 BTU) at a constant temperature of 100 °C (212°F) (at sea level). To condense one kg or (pound) of steam to water, 2257 kJ (970 BTU) must be extracted from the steam.

Temperature-Heat diagram for water :

1-2 Heat added (sensible) to heat the ice from -17.8 °C to 0 °C.
2-3 Heat added (latent heat of fusion) to melt the ice (no changes in temp.).
3-4 Heat added (sensible) to heat the water from 0 °C to 100 °C.
4-5 Heat added (latent heat of evaporation) to vaporize water (no changes in temp.).

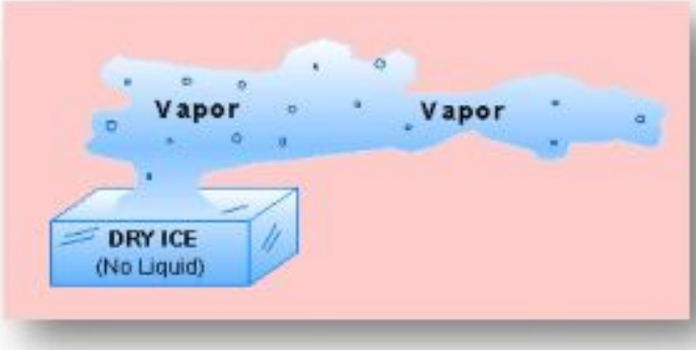


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Latent Heat of Sublimation :

A change in state directly from a solid to a vapour without going through the liquid phase can occur with some substances. The most common example is the use of "dry ice" or solid carbon dioxide when used for cooling. The same process can occur with ice below the freezing point. This process is utilized in some freeze-drying processes at extremely low temperatures and deep vacuums. The latent heat of sublimation is equal to the sum of the latent heat of fusion and the latent heat of evaporation.

The latent heat for dry ice is 577 kJ/ kg (248 Btu/lb).



Saturated Liquid :

A liquid is said to be saturated when sufficient heat has been added to raise its temperature to boiling level at the existing pressure. Any increase in heat would result in vaporization, whereas decrease in temperature only brings about a reduction in sensible heat.

When liquid in saturation condition exist, the maximum amount of sensible heat in relation to the pressure under which saturation occurs is said to be held by the liquid. Therefore, heat of the liquid reaches its maximum value when liquid in saturation condition exist.

The boiling or vaporization temperature of a liquid at a particular pressure is referred to as the saturation temperature. This temperature is not only the boiling point of the liquid but is also the condensing point of the vapour.

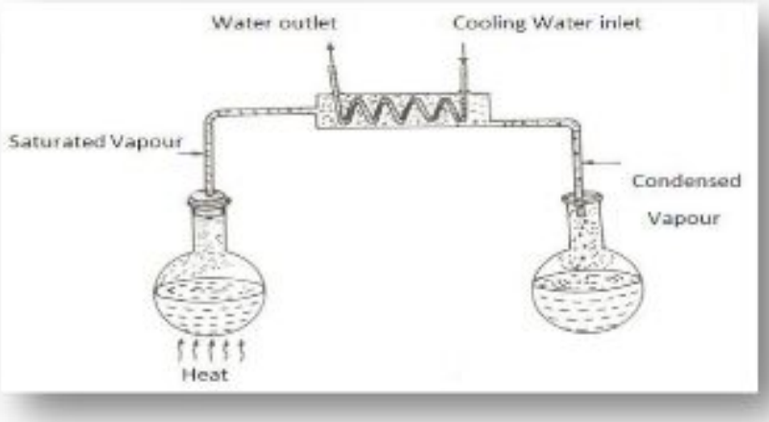
Any liquid which has a temperature lower than the saturation temperature corresponding to its pressure is said to be sub-cooled.

Saturated Vapour :

The vapour given off by a boiling liquid is at the same temperature as the liquid, the temperature of the liquid and the vapour is called the saturation temperature and the vapour is called dry saturated vapour. The vapour contains all the heat that it can hold at the temperature. The vapour is known as dry vapour because it does not contain any liquid particles.

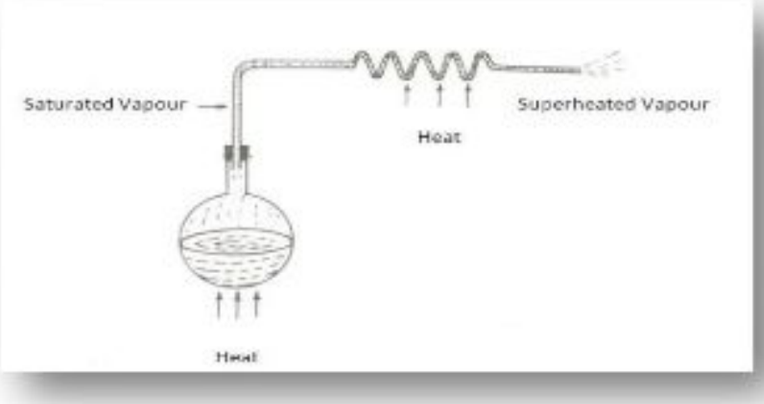
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A mixture of vapour and entrained liquid at the saturation temperature is called wet saturated vapour.



Superheated Vapour :

A vapour which has a temperature higher than saturation temperature corresponding to its pressure is said to be superheated. As long as a vapour is in contact with its liquid it has the same temperature as the liquid . Therefore in order for a vapour to become superheated , it should not be in contact with its liquid or it should not contain any entrained liquid. Superheating occurs as a result of further addition of heat to a dry saturated vapour.



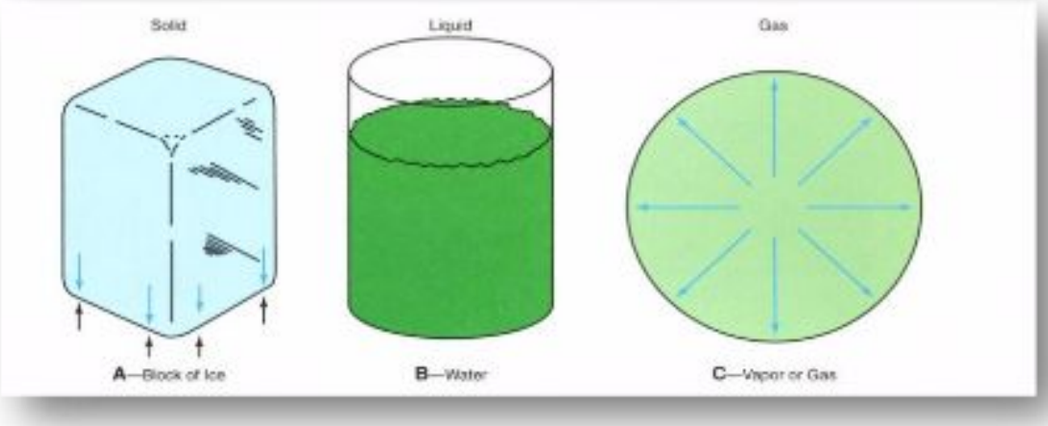
Pressure :

Pressure is the force per unit area. It is expressed in pascals Pa (N/m^2) or kilopascals (kPa) in SI units. It is also expressed in pounds per square inch (psi) in British units.

Substances always push on the surfaces supporting or containing them. A block of ice (a solid) exerts a pressure on its support. If the support were removed, the block would fall to another supporting level.

A liquid exerts a pressure on the sides and bottom of its container. A Gas exerts a pressure on all surfaces of its container.

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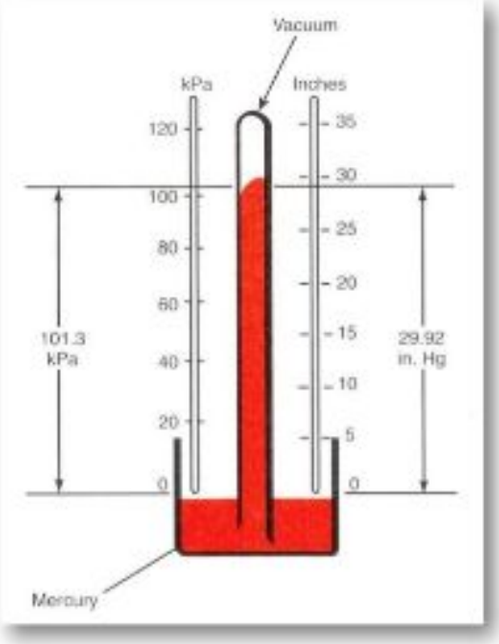
Atmospheric Pressure :



The atmosphere surrounding the Earth is composed of gases, primarily oxygen and nitrogen, extending many kilometers above the surface of the Earth. The weight of that atmosphere pressing down on the Earth creates the atmospheric pressure in which we live. For purposes of standardization and as a basic reference for comparison, the atmospheric pressure at sea level has been universally accepted. It has been established approximately at 101.3 kPa (14.7 psi). This is equivalent to the pressure exerted by a column of mercury 760 mm (29.92 inches) high.

Mercury Barometer :

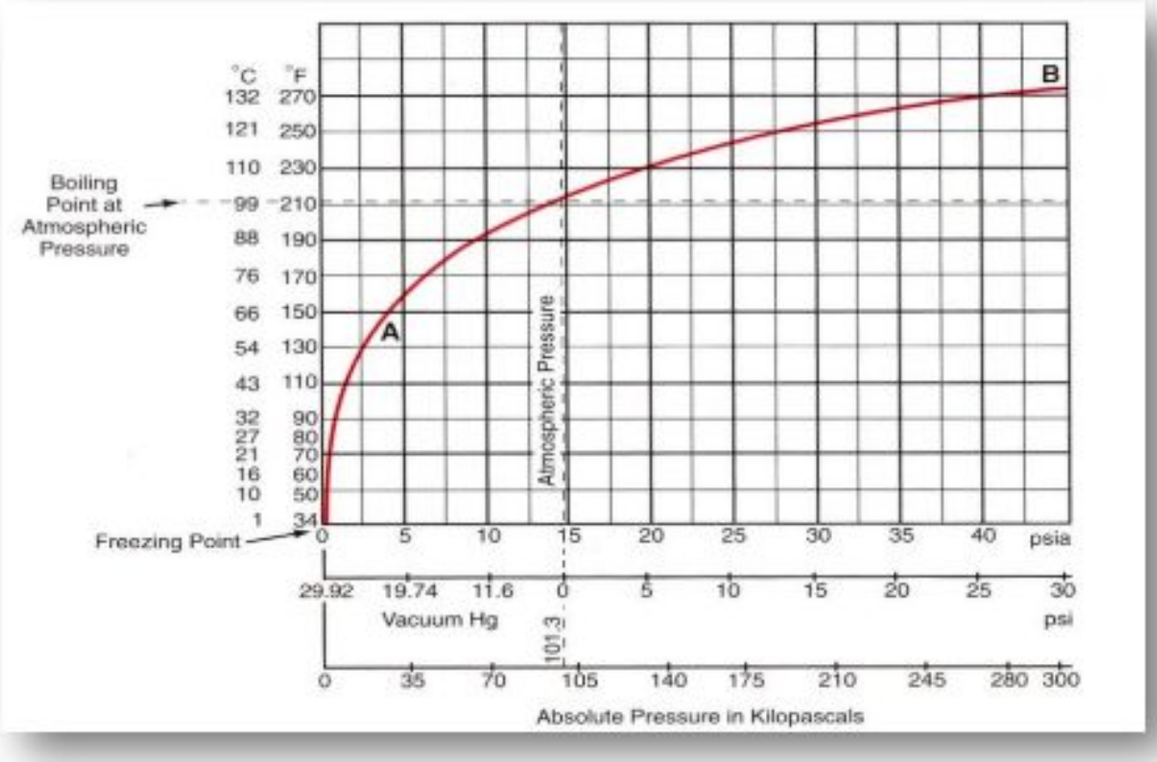
Mercury barometer used for measuring atmospheric pressure. It consist of glass tube closed at one end and open at other end. Fill tube with mercury. Then sealing open end, invert it in container of mercury. When seal is removed, mercury will drop to level corresponding with atmospheric pressure.



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Effect of Pressure on Evaporating (Boiling) Temperature:

The evaporating (boiling) temperature for any liquid is controlled by the pressure placed upon it. Water at atmospheric pressure (101.3 kPa) normally boils at (100 °C) . If the pressure is increased to (311 kPa) , the boiling temperature is raised to (133 °C). If the pressure is lowered to (20 kPa) , the boiling temperature will lowered to (62 °C).

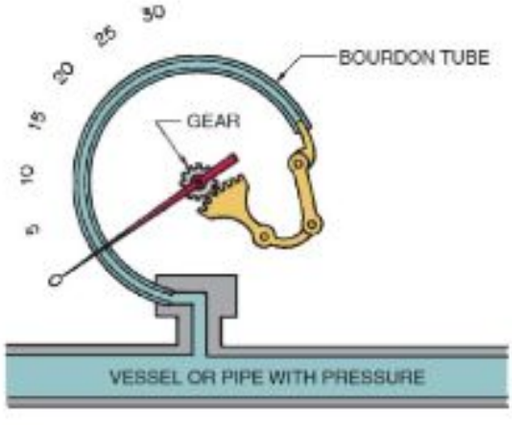


Pressure Gauges :

Measuring pressures in a closed system requires a different method, Bourdon tube gauge used for this purpose.

The Bourdon tube is made of a thin substance such as brass. It is closed on one end, and the other end is fastened to the

pressure being checked. When pressure increases, the tube tends to straighten out. When attached to a needle linkage, pressure changes are indicated.



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Gauge Manifolds :



A gauge manifold includes both high-side gauge and low-side (vacuum) gauge. It allows to check operating pressure, add or recover refrigerant, add oil, and perform other necessary operations.

The gauge on the left (blue) is called a compound gage because it reads below atmospheric pressure and above atmospheric pressure. The right-hand gauge (red) reads high pressure.

Gauge Pressure:



A pressure gauge is calibrated to read 0 regardless of elevation when not connected to a pressure producing source.

A reading of 0 on the gauge is equal to the atmospheric pressure, which is about 14.7 psia (101.3 kPa).
Pressures below 0 are actually negative readings on the gauge, and are usually referred to as inches or (mm) of mercury vacuum.
Compound gauges have two or more pressure scale. One measures pressure below atmospheric pressure, the other measures pressures above atmospheric pressure.

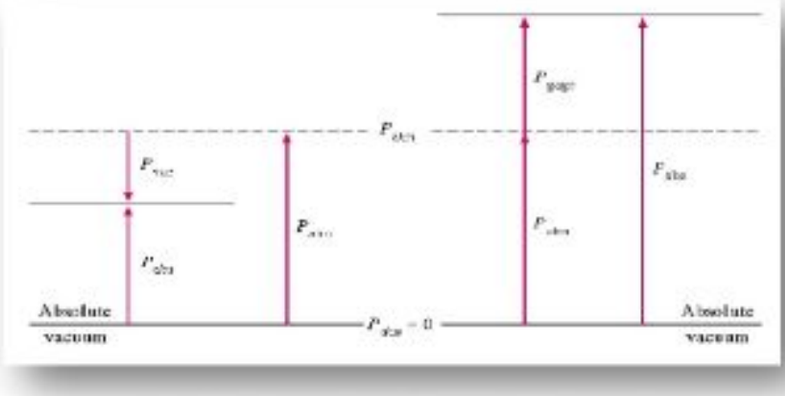
Absolute pressure:

Absolute pressure, is defined as the pressure existing above a perfect vacuum. Therefore in the air around us, absolute pressure and atmospheric pressure are the same.

The absolute pressure of a closed system will always be gauge pressure plus atmospheric pressure.

Absolute pressure = Gauge pressure + Atmospheric pressure

$$P_{abs} = P_{g} + P_{at}$$



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Manometers :

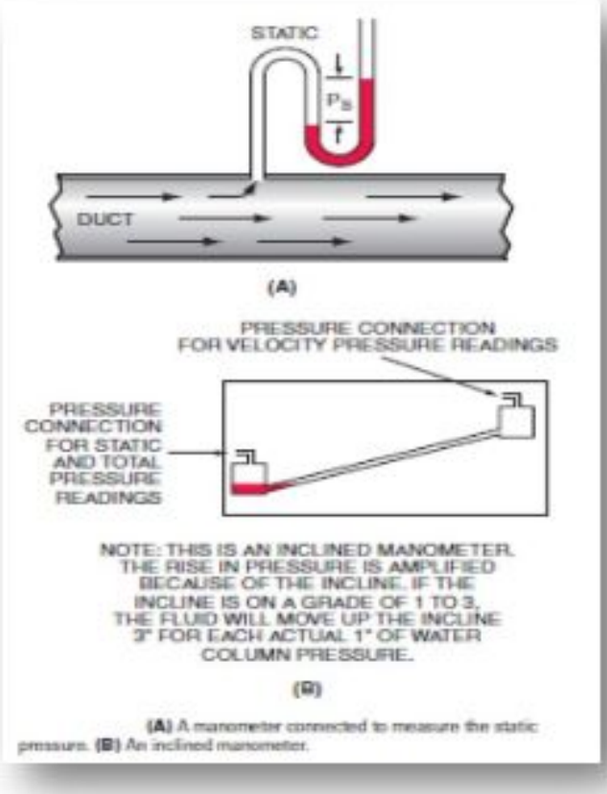


Liquid-column manometers measure pressure by determining the vertical displacement of a liquid of known density in a known gravitational field. Typically they are constructed as a U-tube of transparent material (glass or plastic). The pressure to be measured is applied to one side of the U-tube. If the other (reference) side is evacuated (zero pressure), the manometer measures absolute pressure; if the reference side is open to the atmosphere, it measures gage pressure; if the reference side is connected to some other pressure, the manometer measures the differential between the two pressures. Manometers filled with water and different oils are often used to measure low-range differential pressures.

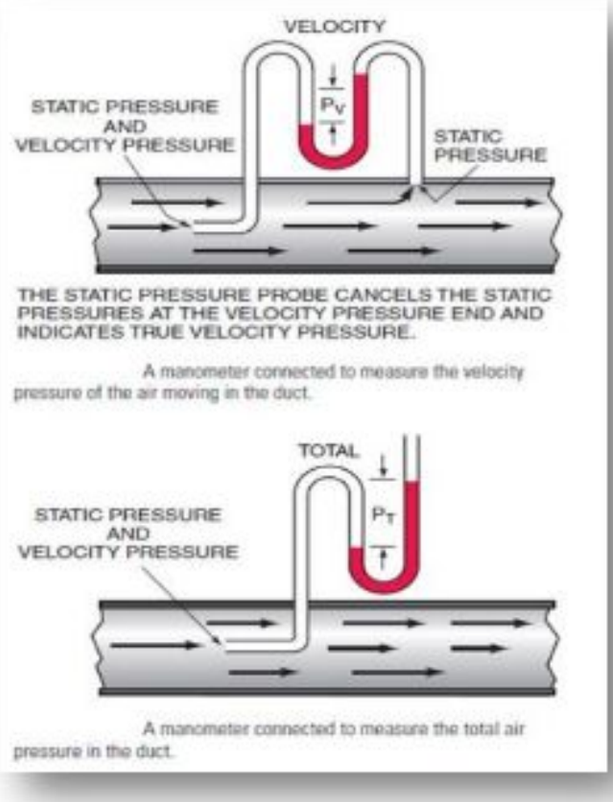


In some low-range instruments, one tube of the manometer is inclined in order to enhance the readability.

Mercury-filled manometers are used for higher range differential and absolute pressure measurements. In the latter case, the reference side is evacuated, generally with a mechanical vacuum pump. Typical full-scale ranges for manometers vary from 2.5 kPa (250 mm of water) to 300 kPa.



(A) A manometer connected to measure the static pressure. (B) An inclined manometer.



A manometer connected to measure the velocity pressure of the air moving in the duct.

A manometer connected to measure the total air pressure in the duct.

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Refrigeration :

Refrigeration may be defined as the process of achieving and maintaining a temperature below that of the surroundings, the aim being to cool some product or space to the required temperature. One of the most important applications of refrigeration has been the preservation of perishable food products by storing them at low temperatures.

Refrigeration systems are also used extensively for providing thermal comfort to human beings by means of air conditioning.

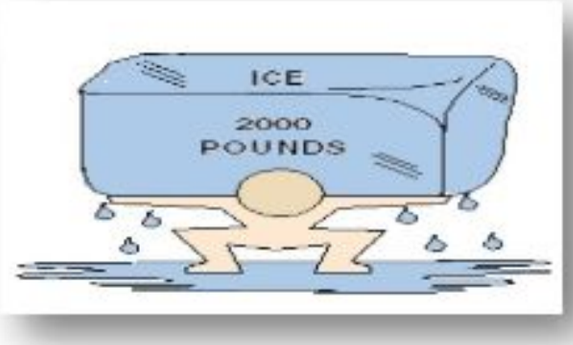
The term refrigeration is commonly associated with something cold. A household refrigerator, for example, keeps food cold. It accomplishes this task by removing heat from the food. Therefore, refrigeration involves the removal of heat. The word cold describes a state of low heat content.

Ton of Refrigeration :

In the English system of units, there is a larger and more convenient measure of the rate of heat flow. It is called a ton of refrigeration. One ton of refrigeration produces the same cooling effect as the melting of 2000 lb of ice over a 24-hour period.

So, 1 ton of refrigeration is defined as the transfer of heat at the rate of 12,000 Btu/hr [3.517 kW].





Air Conditioning :

Full air conditioning implies the automatic control of an atmospheric environment either for the comfort of human beings or animals or for the proper performance of some industrial or scientific process. The adjective 'full' demands that the purity, movement, temperature and relative humidity of the air be controlled, within the limits imposed by the design specification.

It is really correct to talk of air conditioning only when a cooling and dehumidification function is intended, in addition to other aims. This means that air conditioning is always associated with refrigeration.

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Unit 1 questions :

(A): Answer the following questions.

1. At what temperature are the Celsius and Fahrenheit scales equal?
2. Which gauge has two or more pressure scales?
3. What scale is most commonly used on the manometer?
4. What is a definition of BTU?
5. What is specific heat?
6. What is sublimation?
7. How many tons of refrigeration is 36000 Btu/hr?
8. When does a fluid give up latent heat?

(B): Full the blanks with suitable wards.

1. Pressure reading below atmospheric are called _____?
2. Saturation means _____ point ?
3. Temperature above saturation are called _____ ?
4. Sensible heat causes a change of _____ ?
5. Latent heat causes a change of _____ ?
6. Temperatures below saturation are called _____ ?

(C): Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. gauge pressure b. pressure c. absolute zero d. sensible heat e. latent heat f. manometers

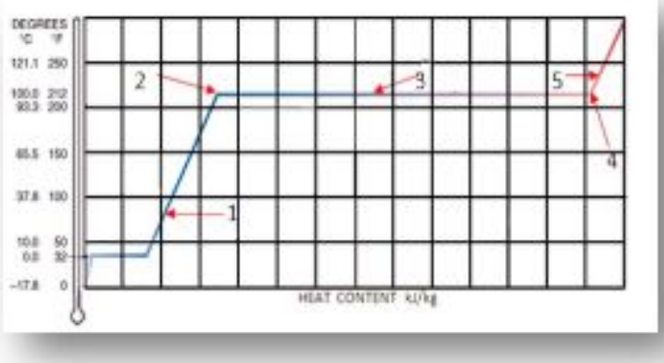
1. The evaporating (boiling) temperature for any liquid is controlled by the _____ place upon it.
2. _____ is that temperature where molecular motion stops.

3. The absolute pressure of a closed system will always be _____plus atmospheric pressure.

4. A change of a substance from a liquid to a vapour, involves the_____ of evaporation.
5. Heat which causes a change in temperature in a substance is called _____.
6. _____are often used to measure low-range differential pressures.

(D): Identify the points in the diagram shown below. Select your answers from the list, then print the letters in the appropriate blanks.

1. _____ a. Saturated vapour
2. _____ b. Wet vapour
3. _____ c. Superheated vapour
4. _____ d. Sub-cooled liquid
5. _____ e. Saturated liquid



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Unit 2

Air Properties:

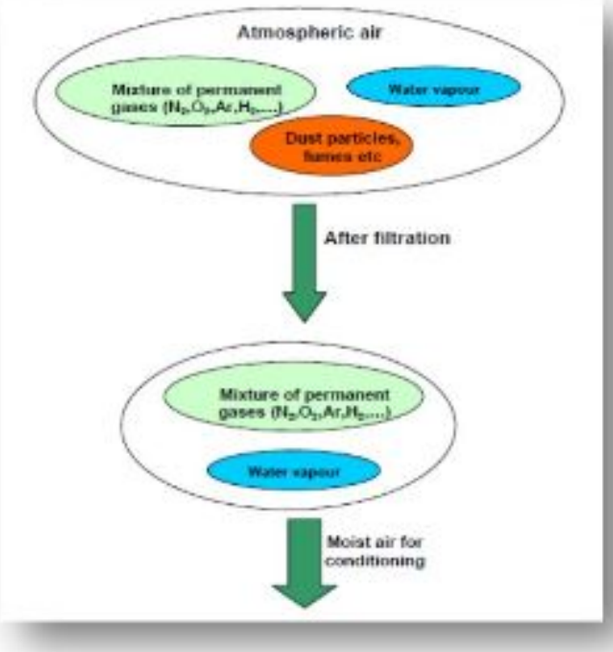
Introduction:

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 concentration of water vapour and pollutants decrease with altitude, and above an altitude of about 10 km, atmospheric air consists of only dry air. The pollutants have to be filtered out before processing the air. Hence, what we process is essentially a mixture of various gases that constitute air and water vapour. This mixture is known as moist 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.

Composition of standard air

Gas	*Proportion (%)*	*Molecular mass*
Nitrogen	78.048	28.02
Oxygen	20.9476	32.00
Carbon dioxide	0.0314	44.00
Hydrogen	0.00005	2.02
Argon	0.9347	39.91



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).

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.

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Dalton's Law of Partial Pressure

This may be stated as follows:

If a mixture of gases occupies a given volume at a given temperature, the total pressure exerted by the mixture equals the sum of the pressures of the constituents, each being considered at the same volume and temperature.

It is possible to show that if Dalton's law holds, each component of the mixture obeys the general gas law. As a consequence, it is sometimes more convenient to re-express the law in two parts"

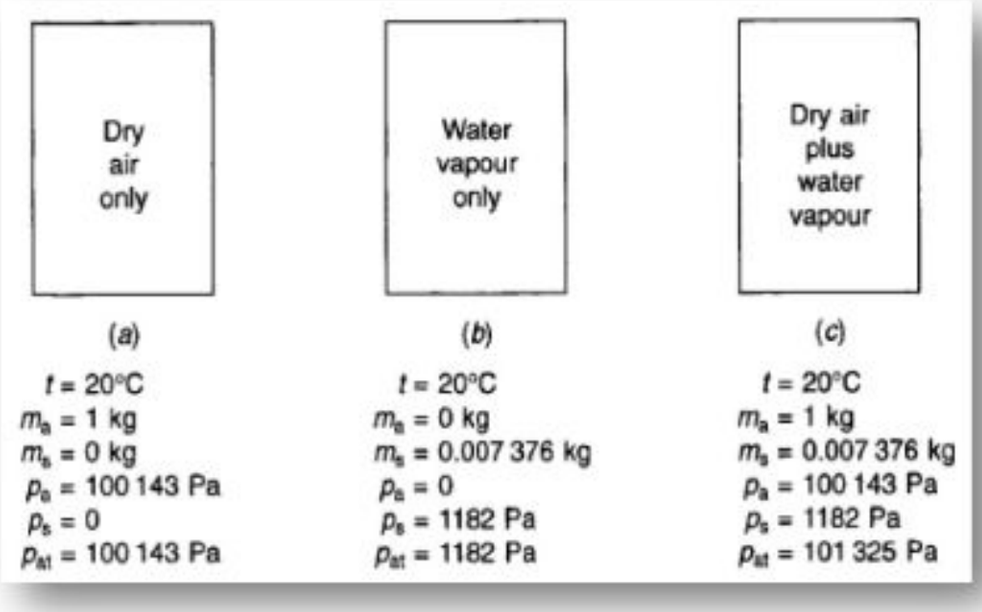
- the pressure exerted by each gas in a mixture of gases is

independent of the presence of the other gases, and

- the total pressure exerted by a mixture of gases equals the

sum of the partial pressures.

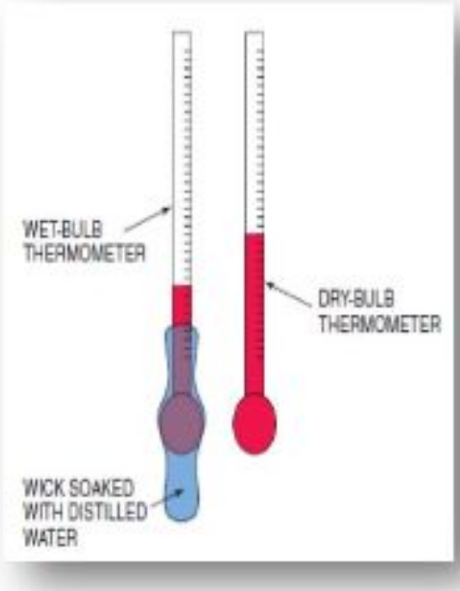
An air-tight container under three different conditions, from which it can be seen that the partial pressures exerted by the water vapour in (b) and (c) are equal, as are those exerted by the dry air in (a) and (c) and, that in (a), (b) and (c), the total pressure equals the sum of the partial pressures. As in the two gas laws already considered, Dalton's law agrees with the results achieved by the kinetic theory of gases and, to some extent, finds substantiation in experiment.



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Dry-Bulb Temperature (DBT)

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



Wet-Bulb Temperature (WBT)

It is a value indicated on an ordinary thermometer, It is measured simply by wrapping a wetted wick around a conventional "dry-bulb" thermometer. Blowing moist air across the wick causes water to evaporate, which depresses the measure temperature below the dry-bulb temperature of the air.

When the moist air is relatively dry, the depression can be very large. As the air becomes more humid, the depression becomes smaller until, at saturation (100% relative humidity), the water will not evaporate and the web-bulb thermometer measures the same as the dry-bulb thermometer.

Psychrometer

Any instrument capable of measuring the psychrometric state of air is called a psychrometer.

The moisture content of air can be checked by using a combination of dry-bulb and wet-bulb temperatures.

Dry-bulb temperature is the sensible-heat level of air and is taken with an ordinary thermometer. Wet-bulb temperature is taken with a thermometer with a wick on the end that is soaked with distilled water.

Both the wet-bulb and dry-bulb temperature readings are obtained at the same time by using an instrument referred to as a sling psychrometer.

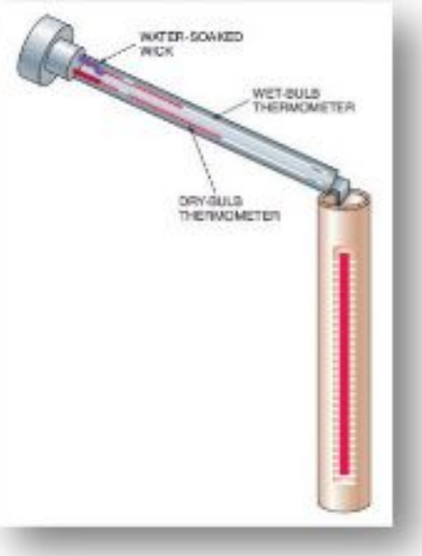
Sling Psychrometer

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

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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.





In the aspirated psychrometer, the thermometers remain stationary, and a small fan, blower or syringe moves the air across the thermometer bulbs.



Electronic psychremeter



Electric psychrometer with a small fan

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.

Of course, since from its definition, the dew point temperature is the saturation temperature corresponding to the vapour pressure of water vapour.



Instrument for determining dew point temperature

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Specific Volume

This is the volume in cubic meters of one kilogram of dry air mixed with g kilograms of water vapour. In the mixture each constituent occupies the same volume and is at the same temperature, but each exerts its own partial pressure. By Dalton's law the sum of these partial pressures is the total (barometric) pressure of the mixture.

The general gas law, may be transposed to express the specific volume:

$$v = \frac{RT}{p}$$

where

v = the specific volume m^3/kg.

R = a constant of proportionality.

T = the absolute temperature K.

p = the pressure Pa.

Moisture Content or (Specific Humidity , Humidity Ratio)

Moisture content is defined as the mass of water vapour in kilograms which is associated with one kilogram of dry air in an air-water vapour mixture. It is sometimes called specific humidity or humidity ratio.

$$W = \frac{\text{kg of water vapour}}{\text{kg of dry air}}$$

$$W = 0.622 \frac{p_s}{(p_{at} - p_s)}$$

Ps = vapour pressure

P_{at} = atmospheric (barometric) pressure

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Relative Humidity

It is defined as the ratio of the partial pressure of the water vapour in moist air at a given temperature, t, to the partial pressure of saturated water vapour in air at the same temperature, t.

$$\phi = \frac{p_s \text{ at a given temperature}}{p_{ss} \text{ at the same temperature}} \times 100$$

Ps = vapour pressure

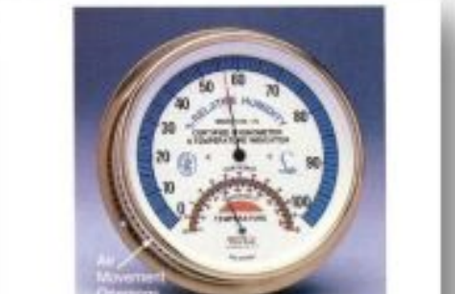
Pss = saturated vapour pressure

Humidity Measurement

A hygrometer is an instrument used to measure moisture in the air. The operation of these instruments depends upon the use of some moisture-absorbing substance, these substance change their shape or size, depending upon the relative humidity of the atmosphere. Human hair, wood, and fibers may be used.

It is also possible to measure relative humidity electronically, using a substance in which the electrical conductivity changes with moisture content.

The electronic instrument shown measures temperature, relative humidity, and dew point.



Wall-type hygrometer and temperature indicator is calibrated in percent of relative humidity.



Enthalpy

Enthalpy (h) is a thermodynamic property, which serves as a measure of heat energy. It is the measurement of the heat content of a substance used in psychrometrics to find the amount of heat necessary for various processes.

As air is heated or cooled, the heat content of the air changes. When cooled, the air's heat content decreases, and when heated, the air's heat content increases. Enthalpy of air is the measure of heat content in KJ/kg of air.

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Unit 2 questions :

(A): True or False:

1. The maximum amount of moisture air can hold depends upon its temperature and barometric pressure.
2. All specific psychrometric properties of moist air are based on unit mass of dry air.
3. Dalton's law stated that the total pressure exerted by the mixture equal the sum of the pressures of the constituents.
4. Atmospheric air is a mixture of many gases plus a number of pollutants.
5. Dry bulb temperature of moist air is always lower than wet bulb temperature.

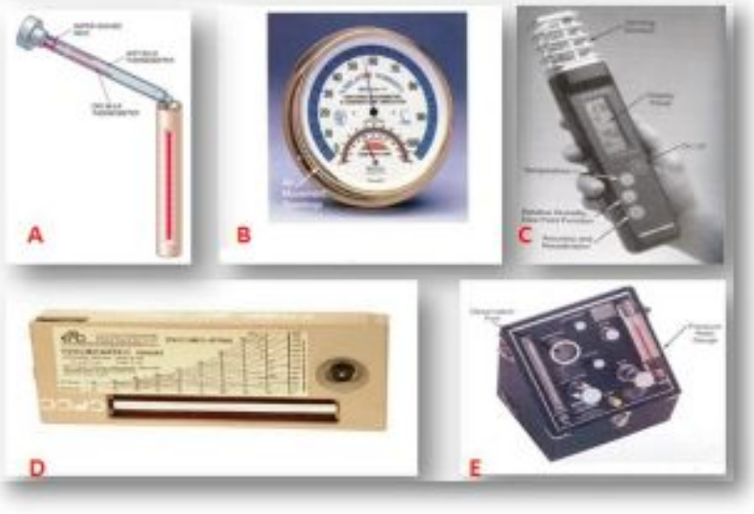
(B): Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. saturated air b. psychrometer c. hygrometer d. water vapour e. dewpoint temperature

1. Atmospheric air is a mixture of many gases plus _____ .
2. When the moisture content is maximum, then the air is known as _____ .
3. Any instrument capable of measuring the psychrometric state of air is called a _____ .
4. The temperature at which the moisture in the air begins to condense is known as_____.
5. A(n) _____ is an instrument used to measure moisture in the air.

(C): Select the instrument to match the descriptions below. Then print the letters in the proper blanks.

_____1. Hygrometer
_____2. Dew-point measurement instrument
_____3. Electric psychrometer
_____4. Electronic hygrometer
_____5. Sling psychrometer



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References:

1. EE IIT, Kharagpur, 40 Lessons on Refrigeration and Air Conditioning, 2008.
2. W.P. Jones, Air Conditioning Engineering, Fifth Edition, Elsevier Butterworth-Heinemann, 2001.
3. Bill Whitman, Bill Johnson, John Tomczyk, Eugene Silberstein, Refrigeration and Air conditioning Technology, Sixth Edition, Delmar, Cengage Learning, 2009.
4. Althouse, Turnquist, Bracciano, Modern Refrigeration and Air Conditioning, The Goodheart-Willcox Company,inc, 2004.
5. G. F. Hundy, A. R. Trott, T. C. Welch, Refrigeration and Air Conditioning, Fourth Edition.

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Unit 3

Psychrometric chart:

Psychrometrics is from the Greek words, "psychro" meaning "cold" and "metrics" meaning "measure of." However, psychrometrics is more than just the measure of cold; it is the science of moist air thermodynamics applied to HVAC systems. With an understanding of psychrometrics, one can use psychrometric charts or to illustrate the changes that occur to air as it goes through the air conditioning processes of heating, cooling, humidifying, and dehumidifying with a minimum of time and effort.

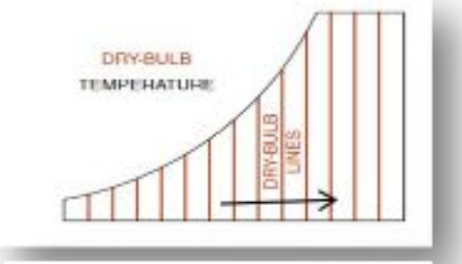
A Psychrometric chart graphically represents the thermodynamic properties of moist air. Standard psychrometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapour pressure or humidity ratio (ordinate). The Left Hand Side of the psychrometric chart is bounded by the saturation line.

Psychrometric charts are readily available for standard barometric pressure of 101.325 kPa at sea level and for normal temperatures (0-50°C). ASHRAE has also developed psychrometric charts for other temperatures and barometric pressures (for low temperatures: -40 to 10 °C, high temperatures 10 to 120 °C and very high temperatures 100 to 120 °C)

Dry Bulb Temperature (°C)

The straight vertical lines are dry bulb temperatures.

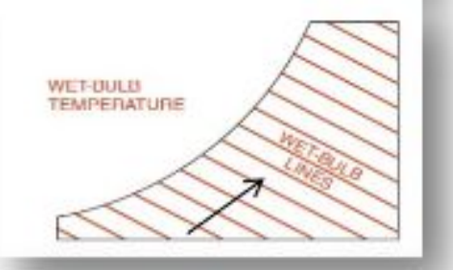
Arrow shows direction of increasing dry bulb temperature.



Wet Bulb Temperatures (°C)

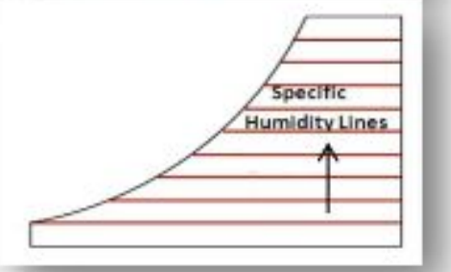
The wet bulb lines run at about a 30 degree angle across the chart.

Arrow shows direction of increasing wet bulb temperature.



Specific Humidity (g/kg dry air)

the specific humidity lines run horizontally at right angles to the dry bulb lines.



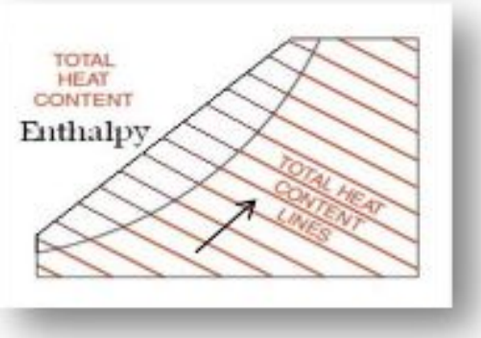
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Enthalpy (kJ/kg)

The enthalpy lines run at inclined lines across the chart.

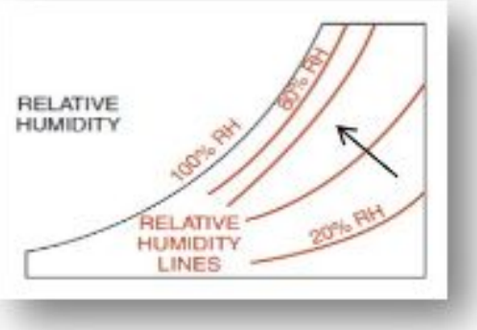
Note that the lines of constant enthalpy are approximately parallel to those of constant wet-bulb, (there is deviation between enthalpy and wet-bulb lines).

The enthalpy scale is on the far left side of the psychrometric chart.



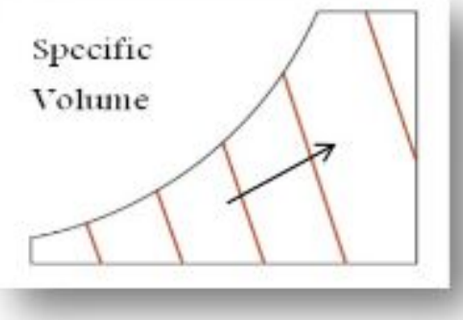
Relative Humidity

The percent relative humidity lines are the curved lines that start on the left side of the chart at the 100 percent saturation line and decrease going to the right side of the chart. On most psych. charts, the designated RH lines are in10% increments starting at the saturation line.



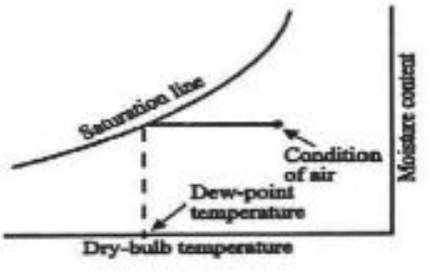
Specific Volume (m^3/kg)

Specific volume lines run across the chart at about a 70 degree angle.



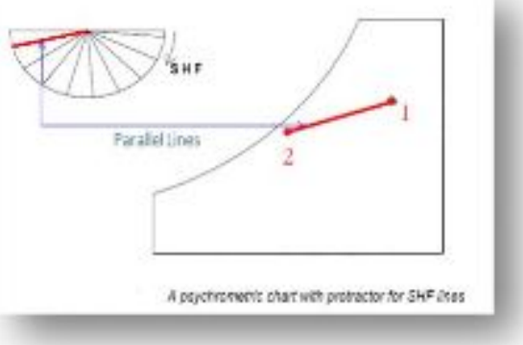
Dew Point Temperature ($^\circ C$)

Dew point temperature is along the curved line on the left side of the chart. This curved line is the 100 percent saturation line. The dew point is where the humidity ratio line intersects the 100 percent saturation curve.

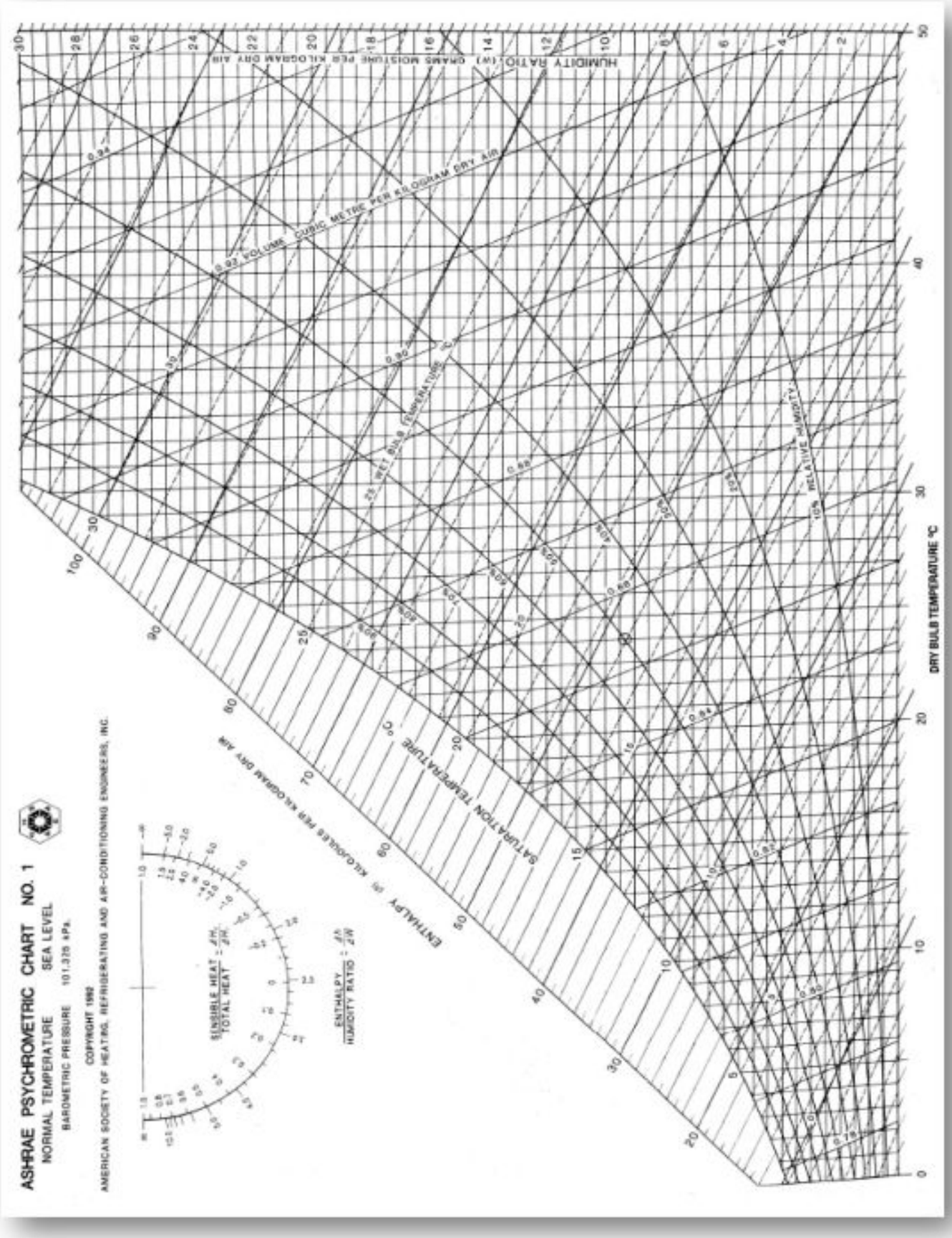


Sensible Heat Factor

In some standard psychrometric charts, a protractor with different values of SHF (sensible heat factor) is provided. The process line is drawn through the initial state point and in parallel to the given SHF line from the protractor .



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Measurement of Psychrometric Properties

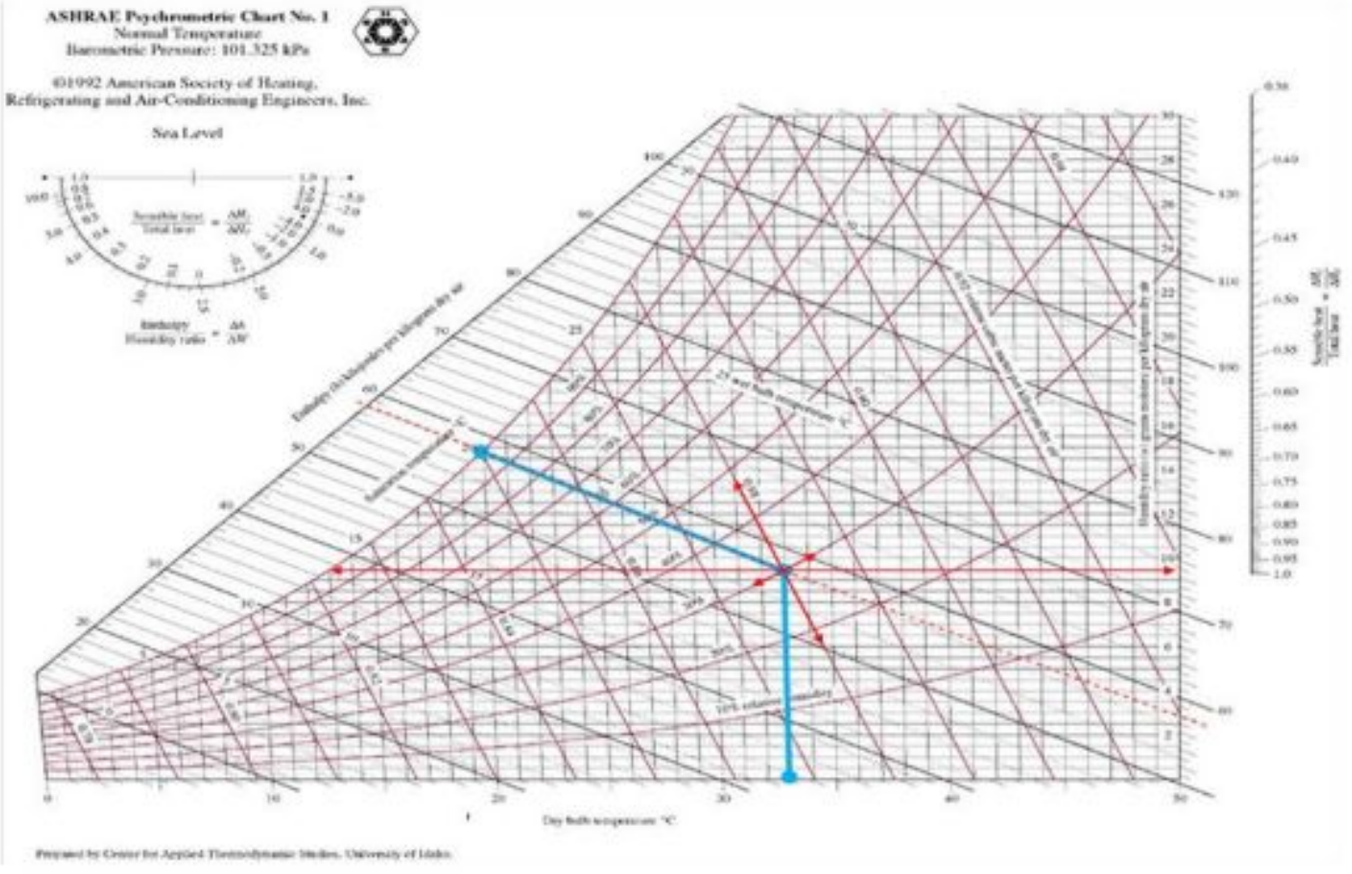
The thermodynamic state of moist air is uniquely fixed if the barometric pressure and two other independent properties are known.

This means that at a given barometric pressure, the state of moist air can be determined by measuring any two independent properties. One of them could be the dry-bulb temperature (DBT), and the other could be the wet-bulb temperature (WBT), as the measurement of these temperatures is fairly simple and accurate.

Thus knowing the dry-bulb and wet-bulb temperatures (or any two properties) from measurements, it is possible to find the other properties of moist air.

Ex: Using the psychrometric chart, find the properties of air at **33 °C, DBT** and **20 °C, WBT**.

RH (Ø)	DP	SP.HUM.(w)	SP. V. (v)	h
30 %	13 °C	9.5 g/kg	0.88 m^3/kg	58 kJ/kg



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Unit 3 questions :

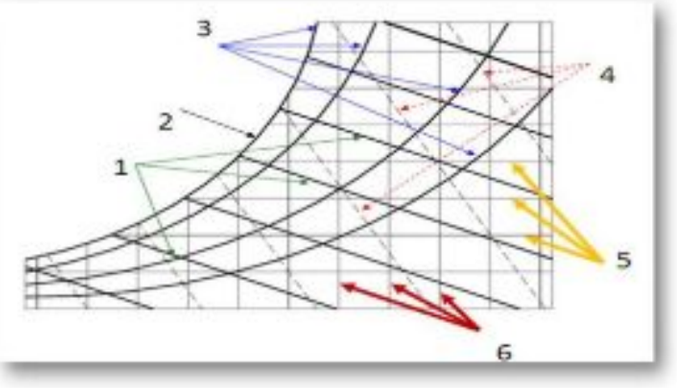
(A) True or False:

1. When the dry bulb temperature is equal to dew point temperature, the relative humidity of air-water mixture is 100%.
2. Wet bulb temperature is always lower than dry bulb temperature, but equal to dew point temperature.
3. Standard psychrometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapour pressure or humidity ratio (ordinate).
4. In some standard psychrometric charts, a protractor with different values of SHF (sensible heat factor) is provided.
5. The minimum number of independent properties to be specified for fixing the state of moist air is one.

(B) Identify the lines of the psychrometric chart shown below . Select your answers from the list, then print the letters in the appropriate blanks.

1. _____
2. _____
3. _____
4. _____
5. _____
6. _____

a. Specific volume
b. Relative humidity
c. Dry bulb temperature
d. Saturation line
e. Specific humidity
f. Enthalpy



(C) Using the psychrometric chart, find the proper values needed to fill in the blanks spaces.

	DBT (°C)	WBT (°C)	RH(Ø) %	DP (°C)	SP. HU (g/kg)	h (kJ/kg)	SP.V (m^3/kg)
A	36		60%				
B						70	0.88

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References:

1. EE IIT, Kharagpur, 40 Lessons on Refrigeration and Air Conditioning, 2008.
2. W.P. Jones, Air Conditioning Engineering, Fifth Edition, Elsevier Butterworth-Heinemann, 2001.
3. Bill Whitman, Bill Johnson, John Tomczyk, Eugene Silberstein, Refrigeration and Air conditioning Technology, Sixth Edition, Delmar, Cengage Learning, 2009.
4. Arora, Refrigeration and Air Conditioning, PHI Learning Private Limited, 2010.

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Unit 4

Psychrometric Processes :

Introduction

Psychrometric chart provides a picture of the way in which the state of moist air alters as an air conditioning process takes place or a physical change occurs. Familiarity with the psychrometric chart is essential for a proper understanding of air conditioning.

Any point on the chart is termed a state point, the location of which, at a given barometric pressure, is fixed by any two of the psychrometric properties.

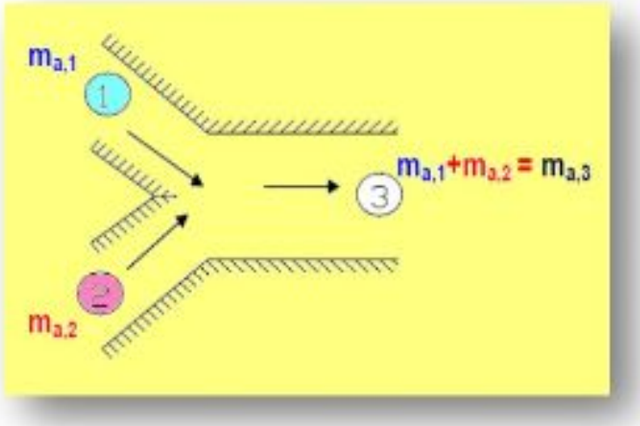
In the design and analysis of air conditioning plants, the fundamental requirement is to identify the various processes being performed on air. Once identified, the processes can be analyzed by applying the laws of conservation of mass and energy.

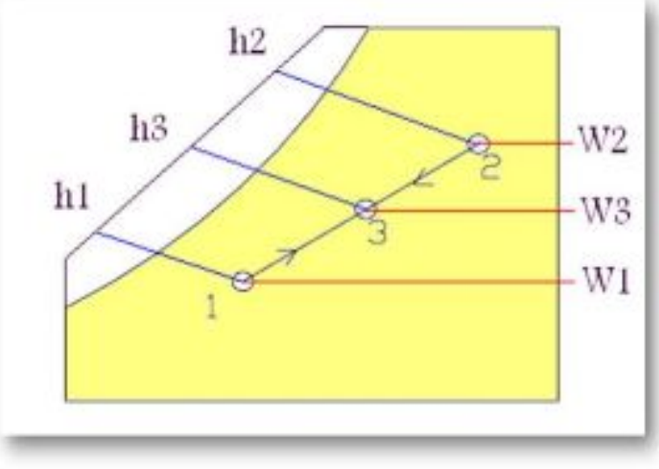
All these processes can be plotted easily on a psychrometric chart. This is very useful for quick visualization and also for identifying the changes taking place in important properties such as temperature, humidity ratio, enthalpy etc.

Mixing of Air Streams

Figures shows what happens when two airstreams meet and mix adiabatically. Moist air at state 1 mixes with moist air at state 2, forming a mixture at state 3.

This adiabatic mixing of two moist air streams takes place with no condensation of moisture





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The principle of the conservation of mass allows two mass balance equations to be written:

$ma_1 + ma_2 = ma_3$ for the dry air

$w_1 ma_1 + w_2 ma_2 = w_3 ma_3$ for the associated water vapour

Hence:

$$(w_1 - w_3)\, ma_1 = (w_3 - w_2)\, ma_2$$

Therefore:

$$\frac{ma_1}{ma_2} = \frac{W3 - W2}{W1 - W3}$$

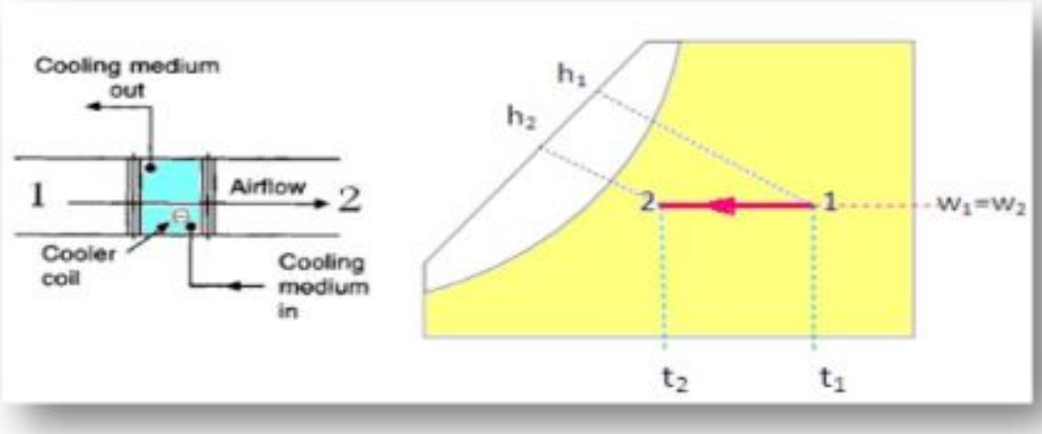
Similarly, making use of the principle of the conservation of energy,

$$\frac{ma_1}{ma_2} = \frac{h3 - h2}{h1 - h3}$$

A principle can be stated for the expression of mixture states, when two airstreams mix adiabatically, the mixture state lies on the straight line which joins the state points of the constituents, and the position of the mixture state point is such that the line is divided inversely as the ratio of the masses of dry air in the constituent airstreams.

Sensible Cooling

During this process, the moisture content of air remains constant but its temperature decreases as it flows over a cooling coil.



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For moisture content to remain constant, the surface of the cooling coil should be dry and its surface temperature should be greater than the dew point temperature of air. If the cooling coil is 100% effective, then the exit temperature of air will be equal to the coil temperature. However, in practice, the exit air temperature will be higher than the cooling coil temperature.

The heat transfer rate during this process is given by:

$$Q_c = m_a (h_1 - h_2)$$

$$= m_a C_{pm} (T_1 - T_2)$$

Where:

C_{pm} humid specific heat

m_a mass flow rate of dry air

Sensible Heating

During this process, the moisture content of air remains constant and its temperature increases as it flows over a heating coil. The heat transfer rate during this process is given by:

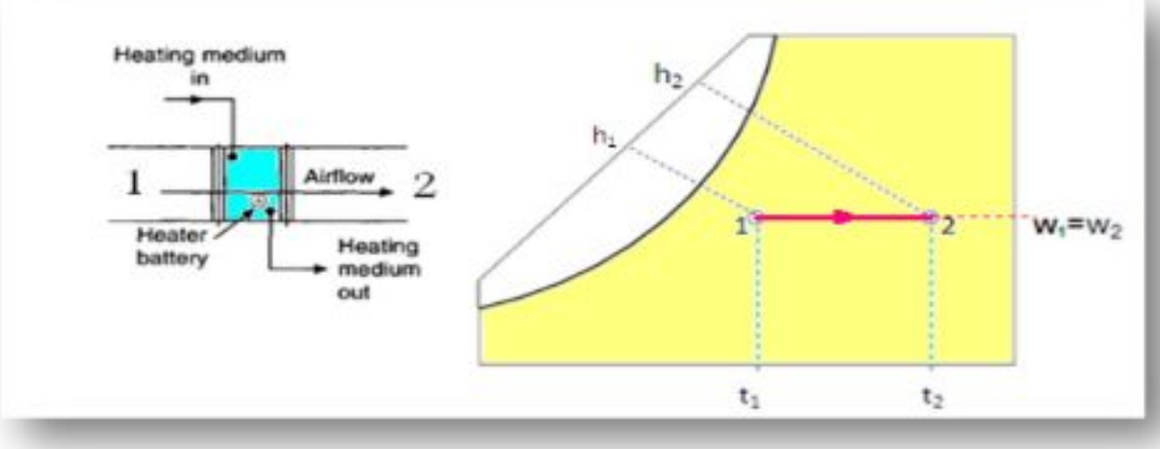
$$Q_h = m_a (h_2 - h_1)$$

$$= m_a C_{pm} (T_2 - T_1)$$

Where:

C_{pm} humid specific heat

m_a mass flow rate of dry air



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The variations in the physical properties of the moist air, for sensible heating and sensible cooling, are summarized below:

	Sensible heating	Sensible cooling
Dry-bulb	increases	decreases
Enthalpy	increases	decreases
Humid volume	increases	decreases
Wet-bulb	increases	decreases
Percentage saturation	decreases	increases
Moisture content	constant	constant
Dew point	constant	constant
Vapour pressure	constant	constant

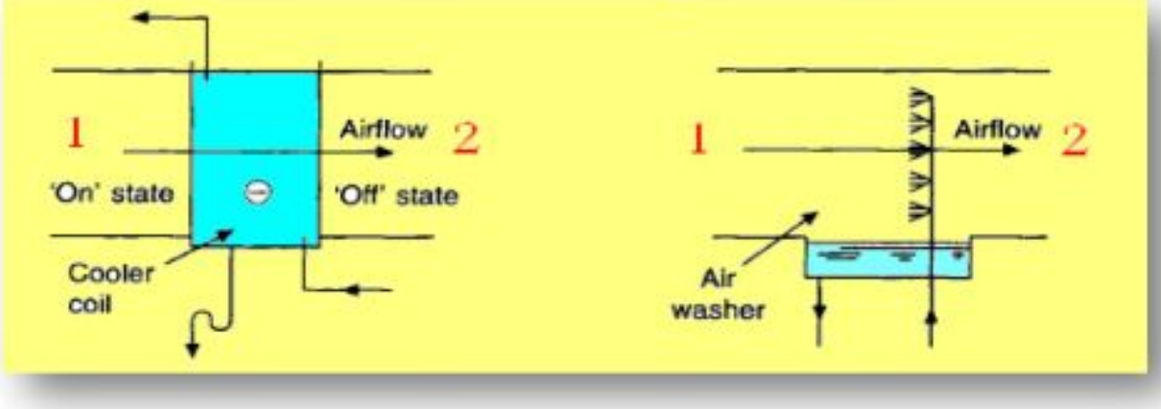
Dehumidification

There are four principal methods whereby moist air can be dehumidified:

- cooling to a temperature below the dew point,
- adsorption,
- absorption,
- compression followed by cooling.

The first method forms the subject matter of our study.

Cooling to a temperature below the dew point is done by passing the moist air over a cooler coil or through an air washer provided with chilled water.

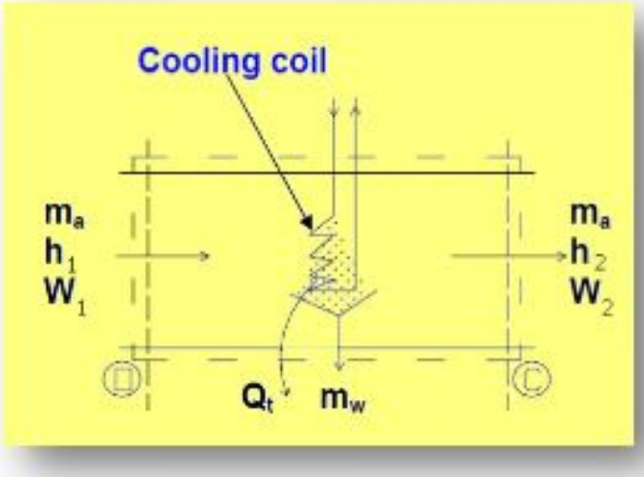


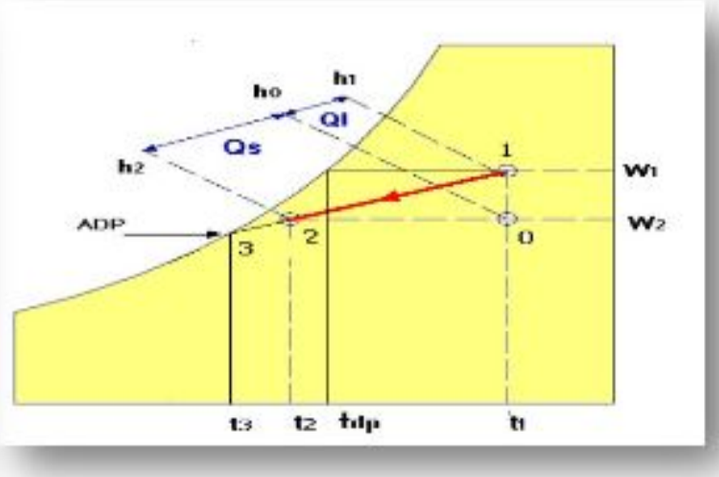
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Cooling and Dehumidification

Since dehumidification is the aim, some of the spray water or some part of the cooler coil must be at a temperature less than the dew point of the air entering the equipment.

In the figure, t_{dp} is the dew point of the moist air 'on' the coil or washer. The temperature t_3, corresponding to the point 3 on the saturation curve, is termed the apparatus dew point. This term is in use for both coils and washers but, in the case of cooler coils alone, t_3 is also sometimes termed the mean coil surface temperature.





the load on the cooling coil, Q_t is given by:

$$Q_t = m_a (h_1 - h_2)$$

It can be observed that the cooling and de-humidification process involves both latent and sensible heat transfer processes, hence, the total, latent and sensible heat transfer rates (Q_t, Q_L and Q_s) can be written as:

$$Q_t = Q_L + Q_s$$

$$Q_L = m_a (h_1 - h_0) = m_a . h_{fg} (w_1 - w_2)$$

$$Q_s = m_a (h_0 - h_2) = m_a . C_{pm} (T_1 - T_2)$$

Where:

C_{pm} humid specific heat

m_a mass flow rate of dry air

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When moist air is cooled below its dew-point by bringing it in contact with a cold surface, some of the water vapor in the air condenses and leaves the air stream as liquid, as a result both the temperature and humidity ratio of air decreases.

This is the process air undergoes in a typical air conditioning system. Although the actual process path will vary depending upon the type of cold surface, the surface temperature, and flow conditions, for simplicity the process line is assumed to be a straight line.

Humidification

This, as its name implies, means that the moisture content of the air is increased. This may be accomplished by either water or steam.

There are three methods of using water as a humidifying agent: the passage of moist air through a spray chamber containing a very large number of small water droplets; its

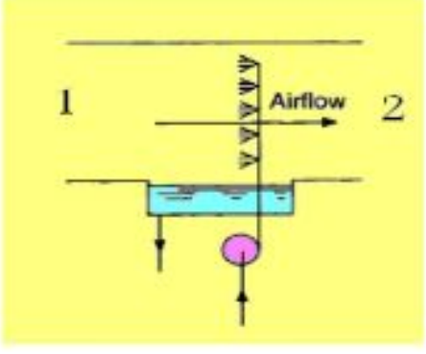
passage over a large wetted surface; or the direct injection of water drops of aerosol size into the room being conditioned.

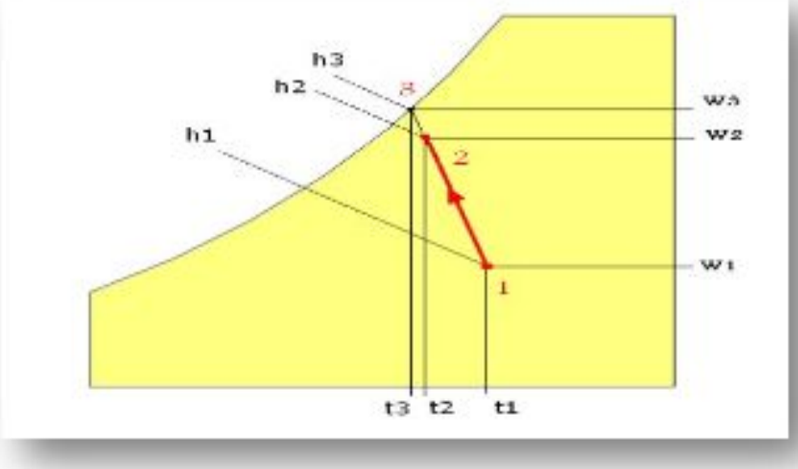
(A variant of this last technique is to inject aerosol-sized droplets into an airstream moving through a duct.)

Cooling and Humidification

The state points 1,2 represents the air before and after the humidification processes. The points 1, 2 and 3 lie on the same straight line, point 3 being obtained by the extension of the line joining 1,2 to cut the saturation curve.

during this process, the air temperature drops and its humidity increases. temperature of sprayed water should be lower than the dry-bulb temperature of air but higher than its wet-bulb temperature **WBT < t_w < t_1**





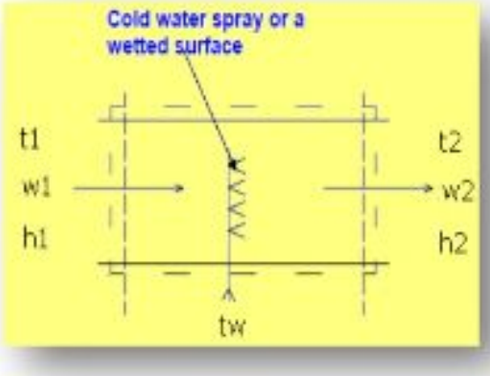
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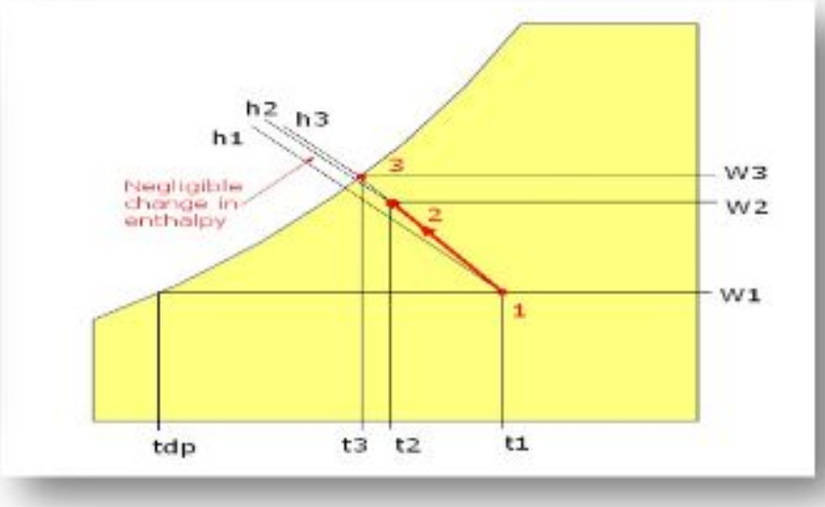
Figure shows that h_2 is greater than h_1. This implies that there is a heat input to the spray water being circulated through the spray chamber.

Here the sensible heat transfer is from air to water and latent heat transfer is from water to air, but the total heat transfer is from water to air, hence, water has to be heated externally. This is the process that takes place in a cooling tower. The air stream extracts heat from the hot water coming from the condenser, and the cooled water is sent back to the condenser.

Cooling and Humidification

During this process, the air temperature drops and its humidity increases. As shown in the figure, this can be achieved by spraying cool water in the air stream. The temperature of water should be lower than the dry-bulb temperature of air but higher than its dew-point temperature to avoid condensation (**$t_{dp} < t_w < t_1$**).





It can be seen that during this process there is sensible heat transfer from air to water and latent heat transfer from water to air. Hence, the total heat transfer depends upon the water temperature.

If the temperature of the water sprayed is equal to the wet-bulb temperature of air, then the net transfer rate will be zero as the sensible heat transfer from air to water will be equal to latent heat transfer from water to air.

If the water temperature is greater than WBT, then there will be a net heat transfer from water to air.

If the water temperature is less than WBT, then the net heat transfer will be from air to water.

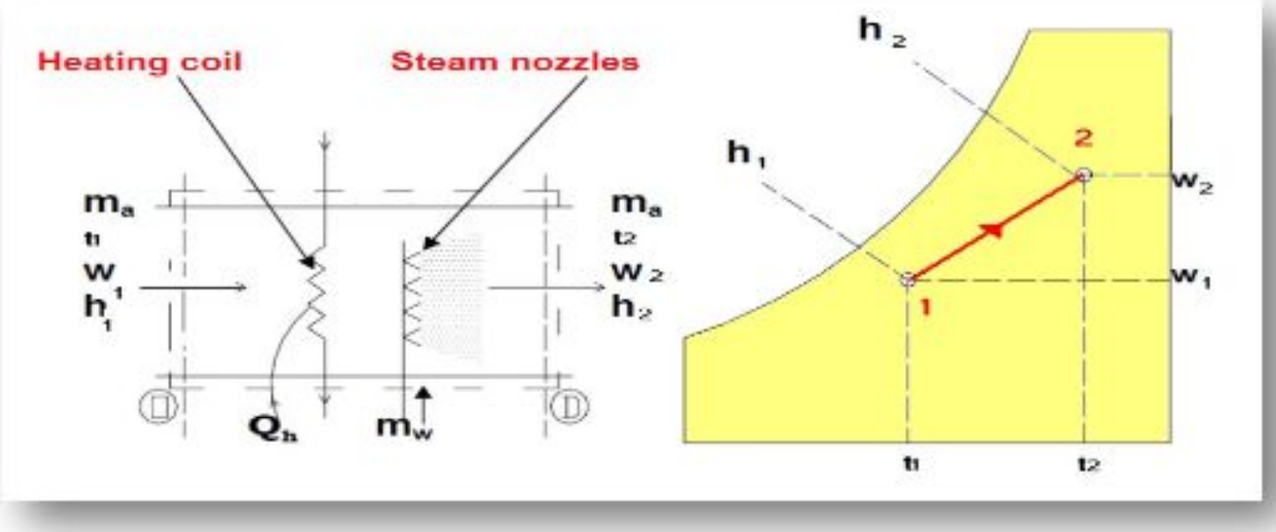
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Under a special case when the spray water is entirely recirculated and is neither heated nor cooled, the system is perfectly insulated and the make-up water is supplied at WBT, then at steady-state, the air undergoes an adiabatic saturation

During this process the WBT remains constant. The process of cooling and humidification is encountered in a wide variety of devices such as evaporative coolers, cooling towers etc.

Heating and Humidification

During winter it is essential to heat and humidify the room air for comfort. As shown in figure, this is normally done by first sensibly heating the air and then adding water vapour to the air stream through steam nozzles.



Mass balance of water vapor for the control volume yields the rate at which steam has to be added, i.e., m_w:

$$m_w = m_a (w_2 - w_1)$$

Where m_a is the mass flow rate of dry air.

From energy balance:

$$Q_h = m_a (h_2 - h_1) - m_w h_w$$

where Q_h is the heat supplied through the heating coil and h_w is the enthalpy of steam.

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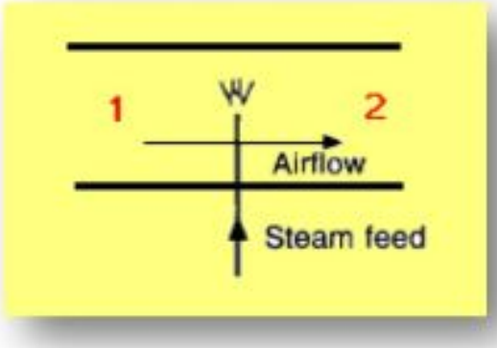
Steam Injection

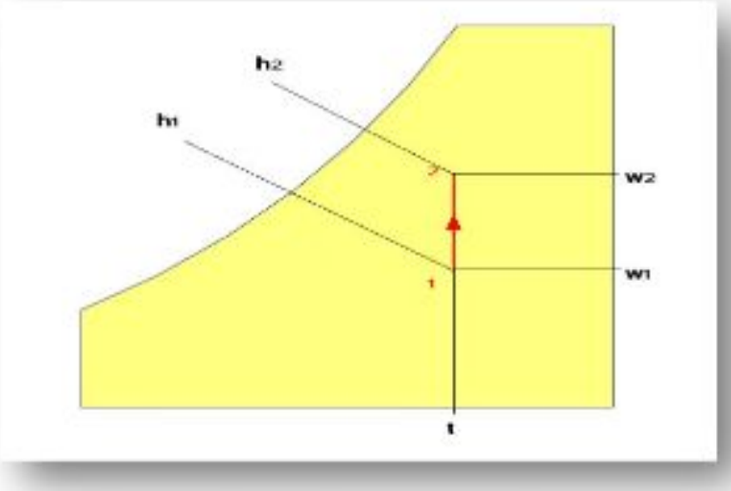
Steam injection may be dealt with by a consideration of a mass and energy balance. If $\mathbf{m_s}$ kg of dry saturated steam are injected into a moving airstream of mass flow 1 kg of dry air per second, then we may write:

$$W_2 = W_a + m_s$$

and

$$h_2 = h_a + h_s$$





If the initial state of the moist airstream and the condition of the steam is known, then the final state of the air may be determined, provided none of the steam is condensed.

The change of state takes place almost along a line of constant dry-bulb temperature between limits defined by the smallest and largest enthalpies of the injected steam, provided the steam is in a dry, saturated condition. Although there is an increase in temperature, it is within the accuracy usually required in practical air conditioning to assume that the change of state following steam injection is up a line of constant dry-bulb temperature.

If the steam is superheated then, of course, the dry bulb temperature of the airstream may increase by any amount, depending on the degree of superheat.

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Unit 4 questions :

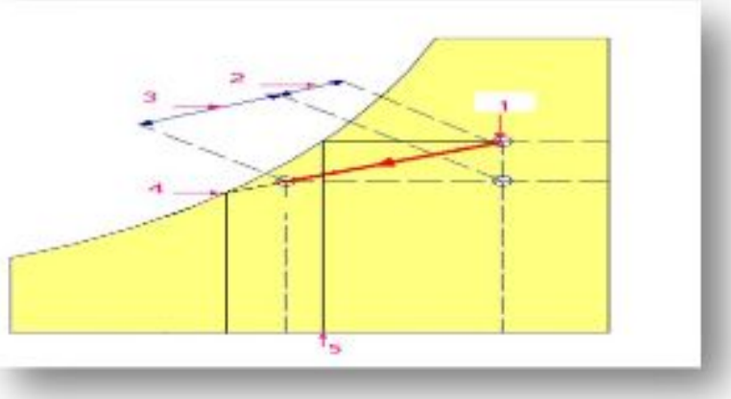
(A): Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. wet bulb temperature **b.** enthalpy **c.** sensible heating **d.** cooling and dehumidification **e.** dew point

1. During _____ process, the moisture content of air remains constant.
2. When moist air is cooled below its _____ , some of the water vapor in the air condenses.
3. During adiabatic saturation process the _____ remains constant.
4. During cooling and humidification process, the _____ of air may increase, decrease or remain constant.
5. During _____ process, the enthalpy of air decreases.

(B): Identify the points in the diagram shown below. Select your answers from the list, then print the letters in the appropriate blanks.

1. _____ a. Latent heat
2. _____ b. Dew point
3. _____ c. Apparatus dew point
4. _____ d. Sensible heat
5. _____ e. Outside air



(C): True or False:

1. When two airstreams mix adiabatically, the mixture state lies on the straight line which joins the state points of the constituents.

2. During sensible cooling of air, dry bulb temperature decreases but wet bulb temperature remains constant.

3. During sensible heating of air, dry and wet bulb temperatures increase but dew point temperature remains constant.

4. During cooling and humidification process, the enthalpy of air may increase, decrease or remain constant depending upon the temperature of the wet surface.

5. During cooling and dehumidification process, the enthalpy of air increases.

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1. EE IIT, Kharagpur, 40 Lessons on Refrigeration and Air Conditioning, 2008.
2. W.P. Jones, Air Conditioning Engineering, Fifth Edition, Elsevier Butterworth-Heinemann, 2001.
3. W. F. Stoecker, W.P. Jones, Refrigeration and air conditioning, Second Edition, McGraw-Hill.
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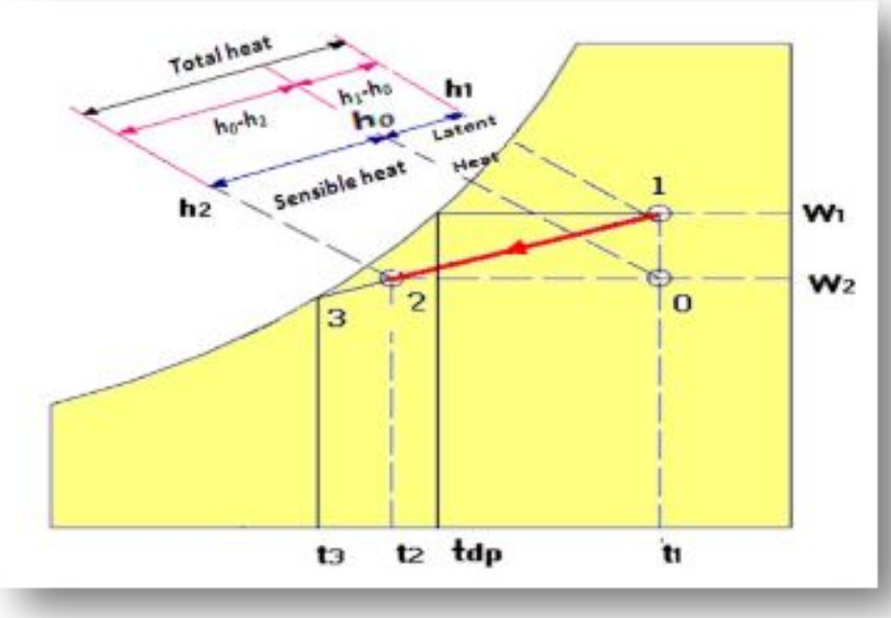
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Unit 5

SHF, BPF, CF, Humidification efficiency:

Sensible Heat Factor (SHF)

The cooling and de-humidification process involves both latent and sensible heat transfer processes, hence, the total heat transfer rate (Q_t) can be written as: $Q_t = Q_L + Q_s$



By separating the total heat transfer rate from the cooling coil into sensible and latent heat transfer rates, a useful parameter called Sensible Heat Factor (SHF) or Sensible Heat Ratio (SHR) is defined.

SHF is defined as the ratio of sensible to total heat transfer rate, i.e.,

$$SHF = \frac{Q_s}{Q_t} = \frac{h_0 - h_2}{h_1 - h_2}$$

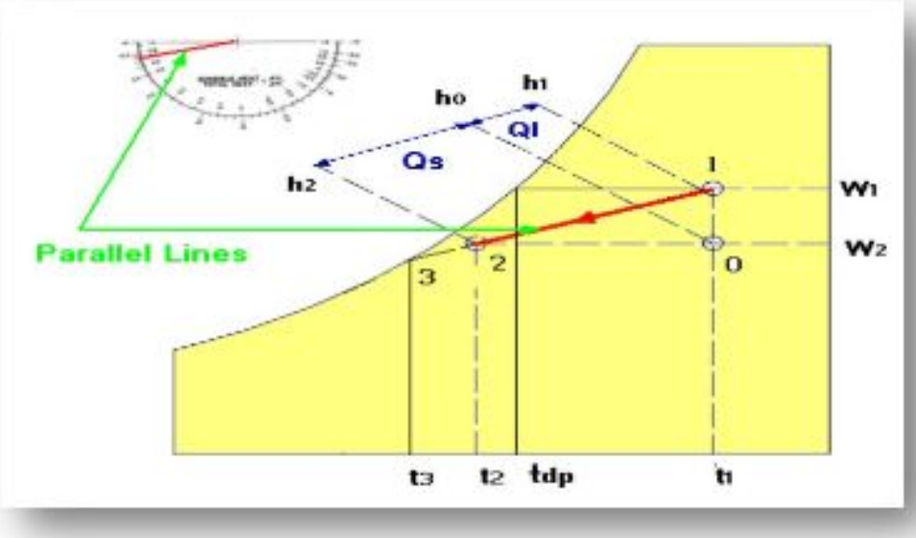
$$= \frac{Q_s}{Q_s + Q_l} = \frac{h_0 - h_2}{(h_0 - h_2) + (h_1 - h_0)}$$

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From the SHF equation, one can deduce that a SHF of 1.0 corresponds to no latent heat transfer and a SHF of 0 corresponds to no sensible heat transfer.

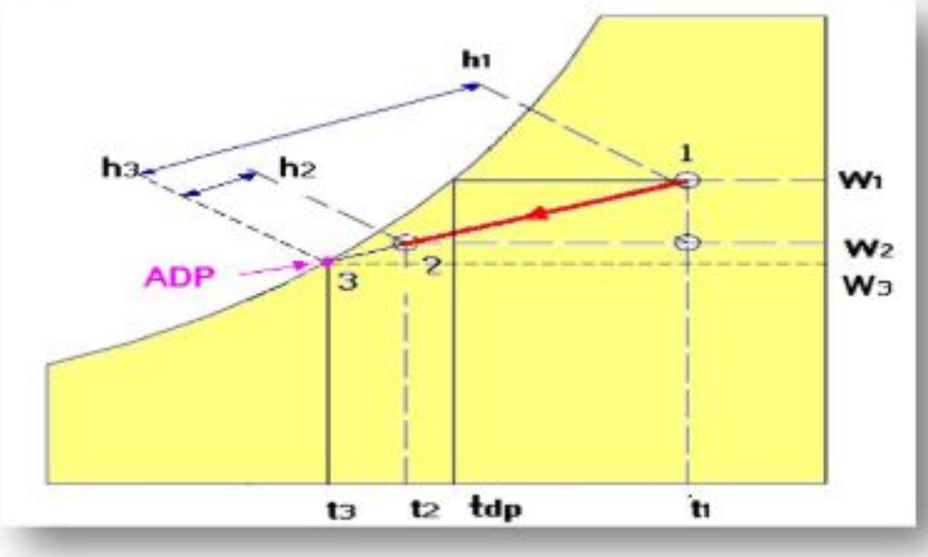
A SHF of 0.75 to 0.80 is quite common in air conditioning systems in a normal dry-climate. A lower value of SHF, say 0.6, implies a high latent heat load such as that occurs in a humid climate.

In some standard psychrometric charts, a protractor with different values of SHF is provided. The process line is drawn through the initial state point and in parallel to the given SHF line from the protractor. Hence, we can draw the cooling and dehumidification line on psychrometric chart if the initial state and the SHF are known.



By pass Factor (BPF)

the temperature t_3 is the effective surface temperature of the cooling coil, and is known as apparatus dew-point (ADP) temperature.



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In an ideal situation, when all the air comes in perfect contact with the cooling coil surface, then the exit temperature of air will be same as ADP of the coil. However, in actual case the exit temperature of air will always be greater than the apparatus dew-point temperature due to boundary layer development as air flows over the cooling coil surface and also due to temperature variation along the fins etc.

Hence, we can define a by-pass factor (BPF) as:

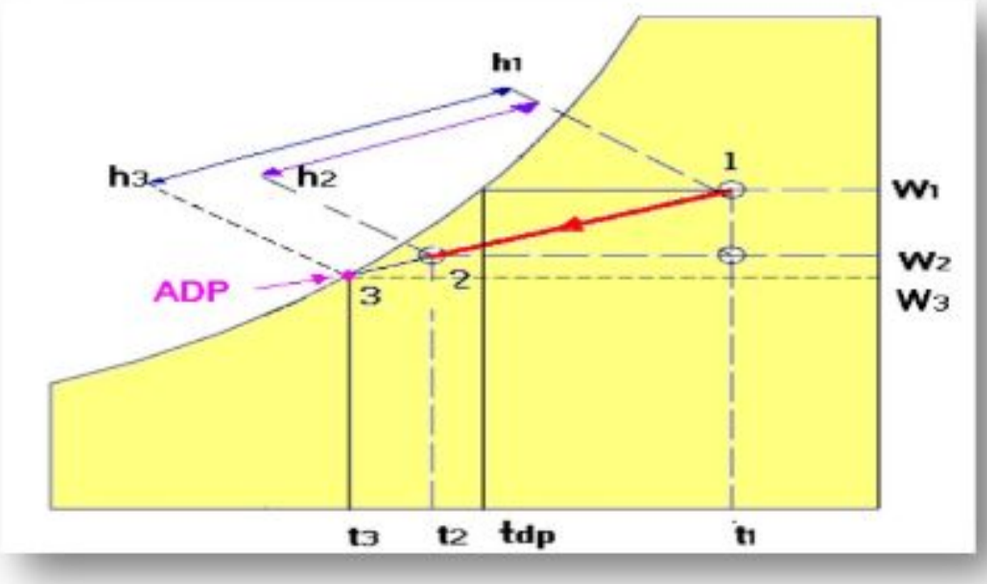
$$BPF = \frac{t_2 - t_3}{t_1 - t_3} = \frac{h_2 - h_3}{h_1 - h_3} = \frac{W_2 - W_3}{W_1 - W_3}$$

It can be easily seen that, higher the by-pass factor larger will be the difference between air outlet temperature and the cooling coil temperature. When BPF is 1.0, all the air by-passes the coil and there will not be any cooling or de-humidification. In practice, the by-pass factor can be increased by increasing the number of rows in a cooling coil or by decreasing the air velocity or by reducing the fin pitch.

Contact Factor (CF)

Contact Factor **(CF) = 1 – BPF (By Pass Factor)**

$$CF = \frac{t_1 - t_2}{t_1 - t_3} = \frac{h_1 - h_2}{h_1 - h_3} = \frac{W_1 - W_2}{W_1 - W_3}$$



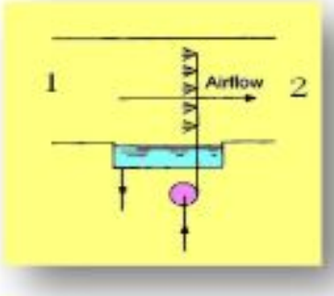
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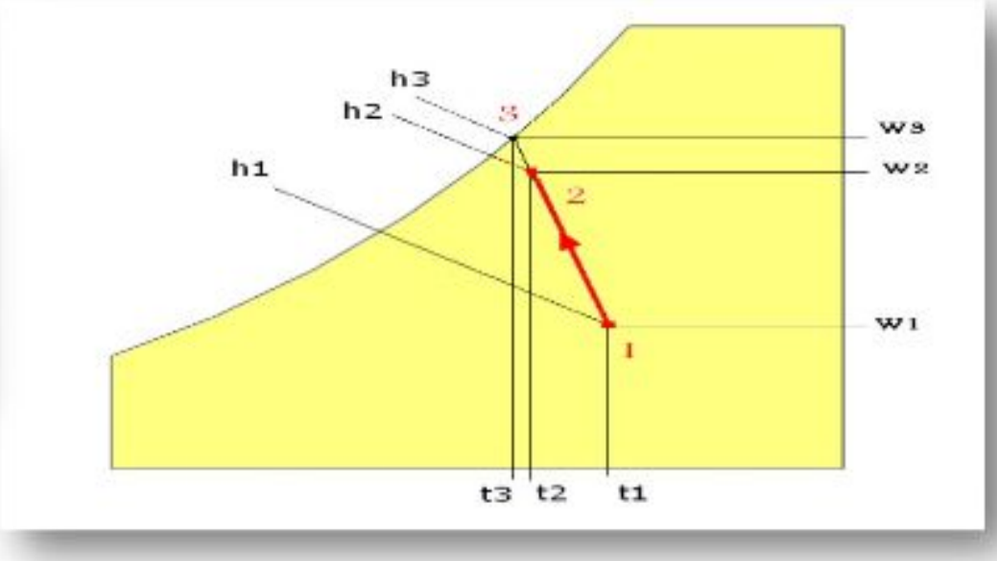
Humidification Efficiency

It is customary to speak of the humidifying efficiency or the effectiveness of an air washer rather than a contact or by-pass factor. There are several definitions, some based on the extent to which the dry-bulb temperature of the entering moist airstream approaches its initial wet-bulb value, and others based on the change of state undergone by the air.

In view of the fact that the psychrometric chart is constructed with mass (moisture content) and energy (enthalpy) as oblique, linear co-ordinates, the most suitable definition to use with the chart is that couched in terms of these fundamentals. There is the further advantage that such a definition of effectiveness, E, is identical with the definition of contact factor, used for cooler coils.

Figure shows an illustration of the change of state experienced by an airstream as it passes through a spray chamber.





The effectiveness of the spray chamber is then defined by

$$E = \frac{h_2 - h_1}{h_3 - h_1}$$

and humidifying efficiency is defined by

$$\eta = 100\ E$$

It is evident that, because moisture content is the other linear co-ordinate of the psychrometric chart and the points 1, 2 and 3 lie on the same straight line, point 3 being obtained by the extension of the line joining 1,2 to cut the saturation curve, then it is

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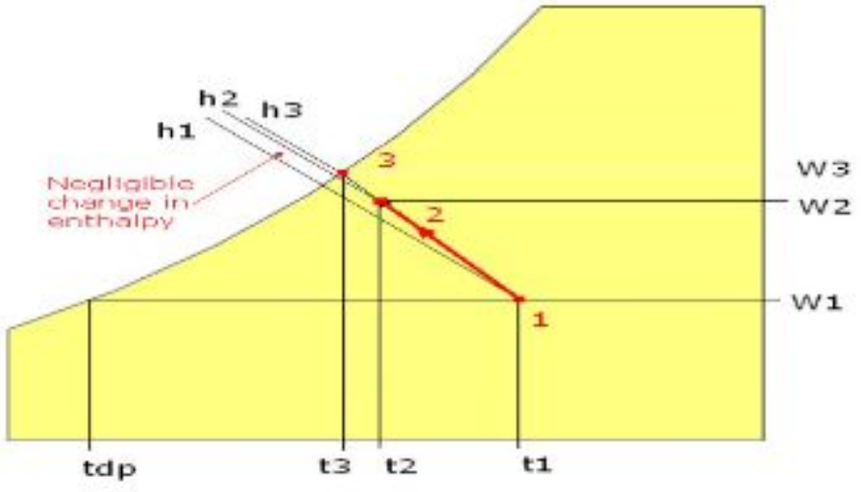
possible to put forward an alternative and equally valid definition of effectiveness, expressed in terms of moisture content:

$$E = \frac{W_2 - W_1}{W_3 - W_1}$$

$\eta = 100\ E$, as before

Although humidifying efficiency is often expressed in terms of a process of adiabatic saturation, this is really a special case, and is so regarded here.

Figure shows a case of adiabatic saturation, in which it can be seen that there is no significant alteration in enthalpy although there is a clear change in moisture content. It can also be seen that a fall in temperature accompanies the rise in moisture content.



One thing is fairly certain though: at the temperatures normally encountered the change of enthalpy during the process is negligible, and so effectiveness must be expressed in terms of change of moisture content.

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Unit 5 questions :

(A). Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. contact factor
b. by pass factor
c. latent heat
d. sensible heat factor

1. The _____ for a sensible heating process is 1.0 .
2. The _____of the coil increases as the velocity of air through the coil increases.
3. By pass factor plus _____ equal 1.0 .
4. From the SHF equation, one can deduce that a SHF of 1.0 corresponds to no _____ transfer .

(B). True or False:

1. The sensible heat factor (SHF) for a sensible cooling process is (0) .
2. As the by-pass factor (BPF) of the cooling coil increases, temperature difference between air at the outlet of the coil and coil ADP decreases.
3. SHF of (0)corresponds to no latent heat transfer and a SHF of (1) corresponds to no sensible heat transfer.
4. The effective surface temperature of the cooling coil, is known as apparatus dew-point (ADP) temperature.
5. The by-pass factor can be increased by increasing the number of rows in a cooling coil.

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References:

1. EE IIT, Kharagpur, 40 Lessons on Refrigeration and Air Conditioning, 2008.
2. W.P. Jones, Air Conditioning Engineering, Fifth Edition Elsevier Butterworth-Heinemann, 2001.
3. W. F. Stoecker, W.P. Jones, Refrigeration and air conditioning, Second Edition, McGraw-Hill.
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5. Arora, Refrigeration and Air Conditioning, PHI Learning Private Limited, 2010.

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Examples Chapter 1

1. **Example:** Convert (400 K) to (°R)

Solution:

$K = \frac{5}{9}\ °R$ ⟵ هذه المعادلة خاصة في ايجاد درجة الحرارة بوحدة الكلفن، لايجادها برانكين نجري حاصل ضرب الطرفين في الوسطين

$°R = \frac{9}{5}\ K$

$°R = \frac{9}{5} \times 400 = 720°R$

2. **Example:** Convert (400 °F) to Celsius (°C) and then to the absolute scale Kelvin (K).

Solution:

Convert from °F to °C:

$℃ = \frac{5}{9} \times (°\text{F} - 32)$

$℃ = \frac{5}{9} \times (400 - 32)$ =204.44 ℃

Convert from °F to K: عندما تم تحويل من الفرنهايت الى السيليزي بعدها يتم استخدام درجة الحرارة السيليزية لايجاد درجة الحرارة بالكلفن

$K = ℃ + 273$

$K = 204.44 + 273 = 477.44\ K$

3. **Example:** How much heat energy is being supplied to the heater at the rate of (0.2 Kg/s) to raise the water's temperature from 25℃ to 45℃ ?

Solution:

$\text{Q} = \text{m} \times \text{C} \times \Delta\text{T}$

$\text{Q} = \text{m} \times \text{C} \times (\text{T}_{\text{out}} - \text{T}_{\text{in}})$

$\text{Q} = 0.2 \times 4.187 \times (45 - 25)$

$\text{Q} = 16.748\ \text{KW}$

4. **Example:** Calculate the temperature of the water coming out of a heater with a flow rate (0.5 kg/s) if the power supplied to the heater is (25 kw) and the water temperature is (20 ℃)? Note that the specific heat of water is (4.187 $KJ/Kg.K$).

Solution:

$$Q = m \times C \times \Delta T$$

$$Q = m \times C \times (T_{out} - T_{in})$$

$$25 = 0.5 \times 4.187 \times (T_{out} - 20)$$

$$11.942 = T_{out} - 20$$

$$\therefore \ T_{out} = 31.942 \ ℃$$

Examples For Chapter 2

1. Example: Calculate the specific volume of dry air at temperature 45ċ and standard atmospheric pressure?

Solution:

$$T = 45 + 273 = 318\ K$$

$$v = \frac{RT}{P}$$

$$v = \frac{287\ \times 318}{101325} = 0.9007\ m^2/kg$$

Note: R → = 287 $J/kg.K$ For dry air

R → = 461 $J/kg.K$ For water vapour

2. Example: Calculate the specific humidity of moist air with a temperature of 30ċ dry bulbs, 24ċ wet bulbs, an atmospheric pressure of 101.325KN/m^2, and a vapor pressure of 2.577 KN/m^2?

Solution:

$$W = 0.622\frac{P_s}{P_{at} - P_s}$$

$$W = 0.622\frac{2.577}{101.325 - 2.577}$$

$$W = 0.0162$$

3. Example: The saturation vapor pressure of a dry bulb at 36 ℃ is (5.940 KN/m^2), while for a wet bulb at 28℃, it is (3.245 KN/m^2). Determine the air specific and relative humidity?

Solution:

$P_{ss} = 5.940\ KN/m^2$

$P_s = 3.245\ KN/m^2$

Specific humidity for air:

$$W = 0.622\frac{P_s}{P_{at} - P_s}$$

$$W = 0.622\frac{3.245}{101.325-3.245} = 0.0206$$

Relative humidity for air:

$$\emptyset = \frac{P_s}{P_{ss}} \times 100\%$$

$$\emptyset = \frac{3.245}{5.940} \times 100\% = 54.63\ \%$$

Example for chapter 4

Ex 1/ Moist air at a temperature of 30℃ dry bulbs and 25℃ wet bulbs, mixing without heat exchange and at standard atmospheric pressure, with other moist air at a temperature of 20℃ dry bulbs and 17℃ wet bulbs. The masses of the dry air in the two cases were 3 kg and 1 kg, respectively. Calculate the specific humidity, enthalpy, and the dry bulb temperature of the mixture using the psychrometric chart.

Solution:

By knowing two properties (1 and 2) of the components of mixed air and using the psychrometric chart, we obtain:

$h_{1=76\ KJ/Kg}$

$W_{1=18\ g/Kg}$

$h_{2=47.7\ KJ/Kg}$

$W_{2=10.8\ g/Kg}$

To calculate the specific humidity (moisture content) from the equation:

$$\frac{m_{a1}}{m_{a2}} = \frac{W_3 - W_2}{W_1 - W_3}$$

$$\frac{3}{1} = \frac{W_3 - 10.8}{18 - W_3}$$

$$W_3 = 16.2\ g/Kg$$

To calculate the enthalpy from the equation:

$$\frac{m_{a1}}{m_{a2}} = \frac{h_3 - h_2}{h_1 - h_3}$$

$$\frac{3}{1} = \frac{h_3 - 47.7}{76 - h_3}$$

$$h_3 = 68.925\ KJ/Kg$$

By intersecting the line connecting points 1 and 2 with the line of specific humidity W_3 or enthalpy h_3, point 3 can be determined, which represents the state of the mixture, and from it the dry bulb temperature T_3 can be measured, or it can be calculated from the equation:

$$T_3 = \frac{m_{a1}T_1 + m_{a2}T_2}{m_{a1} + m_{a2}}$$

$$T_3 = \frac{3 \times 30 + 1 \times 20}{3 + 1}$$

$$T_3 = 27.5\ ℃$$

Ex 2/ السوال3 من اسئلة نصف الفصل الاول لسنة 2023

1.2 m3/s of moist air, initially at a state of 44 ° DBT , 23 °C WBT, its temperature reduced by 26 degrees, calculate :

a. the load on the cooling coil

b. the properties of the air after cooling

DBT (°C)	WBT (°C)	RH (ϕ)	DP (°C)	SP. HU (g/kg)	h (kJ / kg)	SP.V. (m3/kg)
18	14.6	70%	12.5	9	41	0.837

T = 44 – 26 = 18°C

h_1 = 68 KJ/Kg, v_1 =0.911m^3/s , h_2 = 41 KJ/Kg

m = V / v_1

m = 1.2 / 0.911 = 1.317

$Q_c = m(h_1 - h_2)$

Q_c = 1.317 (68 – 41)

Q_c = 35.559 kW

Ex 3/ Calculate the load on a heater (Sensible heating) that raises the temperature (1 m^3/s) of moist air at (12℃) dry bulbs and(7℃) wet bulbs by (25℃).

$T_2 = 12 + 25 = 37℃$

$h_2 = 22.5\ KJ/Kg, \quad v_1 = 0.813\ m^3/s$

$h_2 = 48\ KJ/Kg$

$$m = \frac{V}{v_1} = \frac{1}{0.813} = 1.230\ Kg/s$$

$$Q_h = m(h_2 - h_1)$$

$$Q_h = 1.230(48 - 22.5) = 31.36\ KW$$

Example for chapter 5

Ex 1/ Moist air flowing through a cooling coil at a rate $1\,m^3/s$, initially at a state of 25 ℃ dry bulbs and 18 ℃ wet bulbs, moist air leaves the coil at a temperature of 12 ℃ dry bulbs and a relative humidity of 90% at standard atmospheric pressure. Calculate:

a. apparatus dew point
b. Contact factor (CF)
c. Sensible heat ratio (SHR)
d. Sensible cooling load
e. Latent cooling load

Solution:

Points 1 and 2 are determined and we connect them with a straight line, and the line is extended to intersect the saturation line at point 3 on the psychrometric chart.

$h_1 = 50.5\ KJ/Kg$, $h_2 = 31.8\ KJ/Kg$, $h_3 = 28.3\ KJ/Kg$

$v_1 = 0.858\ m^3/Kg$, $h_0 = 45\ KJ/Kg$

a. apparatus dew point (DPT)= 9.5 ℃
b. $C.F = \frac{h_1 - h_2}{h_1 - h_3}$

$$C.F = \frac{50.5 - 31.8}{50.5 - 28.3} = 0.842$$

c. $\text{SHR} = \frac{h_0 - h_2}{h_1 - h_2}$

$$\text{SHR} = \frac{45 - 31.8}{50.5 - 31.8} = 0.705$$

d. $m = \frac{V}{v_1} = \frac{1}{0.858} = 1.165\ Kg/s$

$Q_C = m \times (h_0 - h_2)$

$Q_C = 1.165 \times (45 - 31.8)$

$= 15.378\ KW$

e. $Q_L = m \times (h_1 - h_0)$

$Q_L = 1.165 \times (50.5 - 45)$

$= 6.41\ KW$

Ex 2/ $2\ m^3/s$ of moist air with a temperature of 25 ℃ dry bulbs and 15℃ wet bulbs enters the spray chamber of the air scrubber. The humidification efficiency of the device was 80% and the temperature of the feed water to compensate for the evaporated water coming from the water liquefaction source was the same as the wet bulb temperature of the enters air. The process takes place in a thermally insulated space and all spray water is recycled. Calculate:

a. The temperature of the air leaving the air scrubber (T_{out})
b. Mass rate of flow of feed water from the liquefaction (m).

Solution:

Since the process takes place in a thermally insulated space and all the spray water is recycled, the process follows a constant wet bulb temperature line.($WBT_1 = WBT_2 = WBT_3$)

بما ان العملية تجري في حيز معزول حراريا وجميع ماء الرش معاد التدوير فأن العلمية تتبع خط ثابت درجة حرارة البصلة الرطبة ($\mathrm{WBT_1 = WBT_2 = WBT_3}$)

$W_1 = 6.5\ g/Kg, \quad W_3 = 10.6\ g/Kg, \quad v_1 = 0.853\ m^3/Kg$

a. $\eta = \frac{W_2 - W_1}{W_3 - W_1} \times 100\%$

$$\frac{80}{100} = \frac{W_2 - 6.5}{10.6 - 6.5}$$

$W_2 = 9.78\ g/Kg$

$\therefore DBT_2 = 17.2$ ℃ من مخطط خواص الهواء

b. $m = \frac{V}{v_1} = \frac{2}{0.853}$

$m = 2.344\ Kg/s$

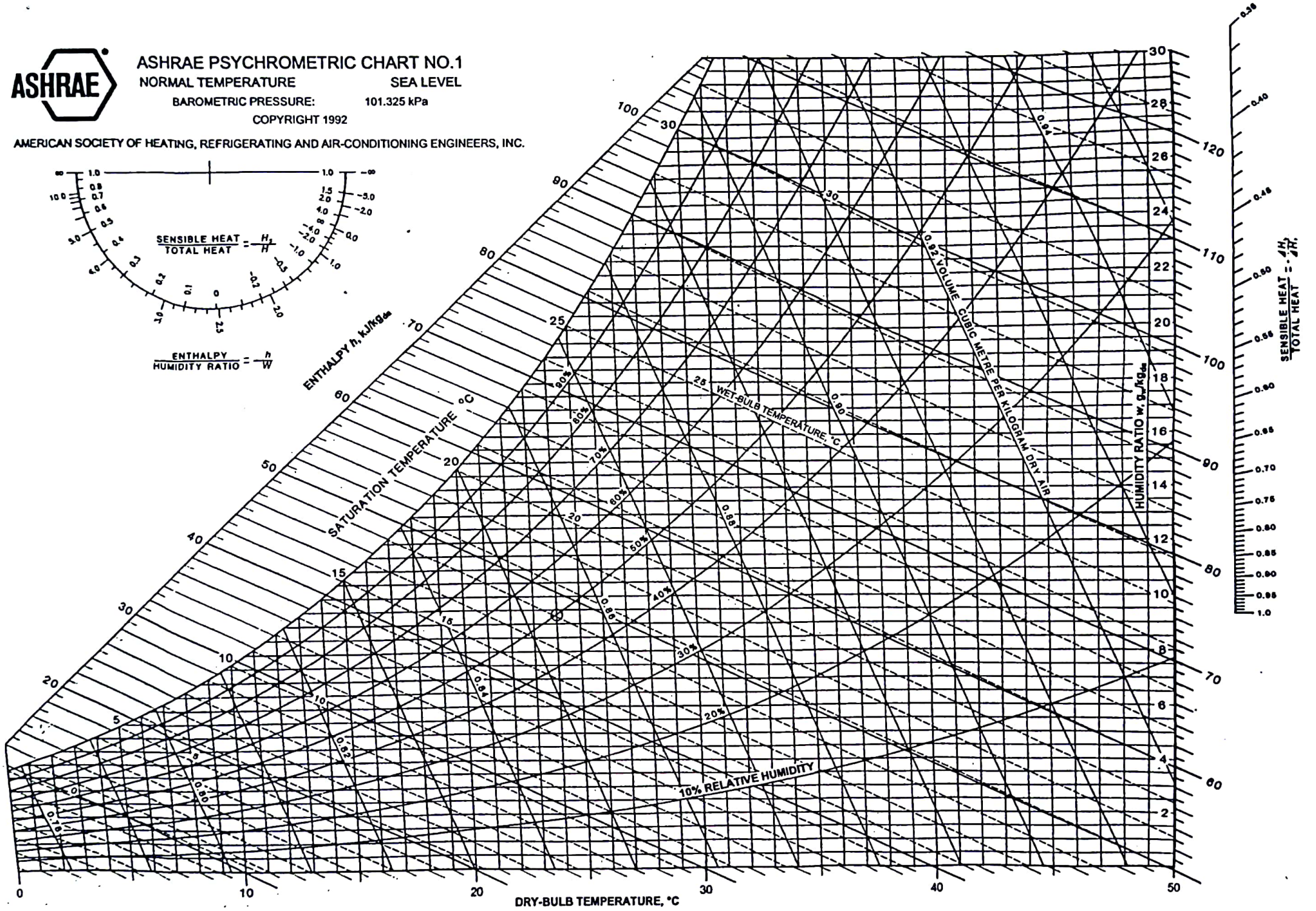


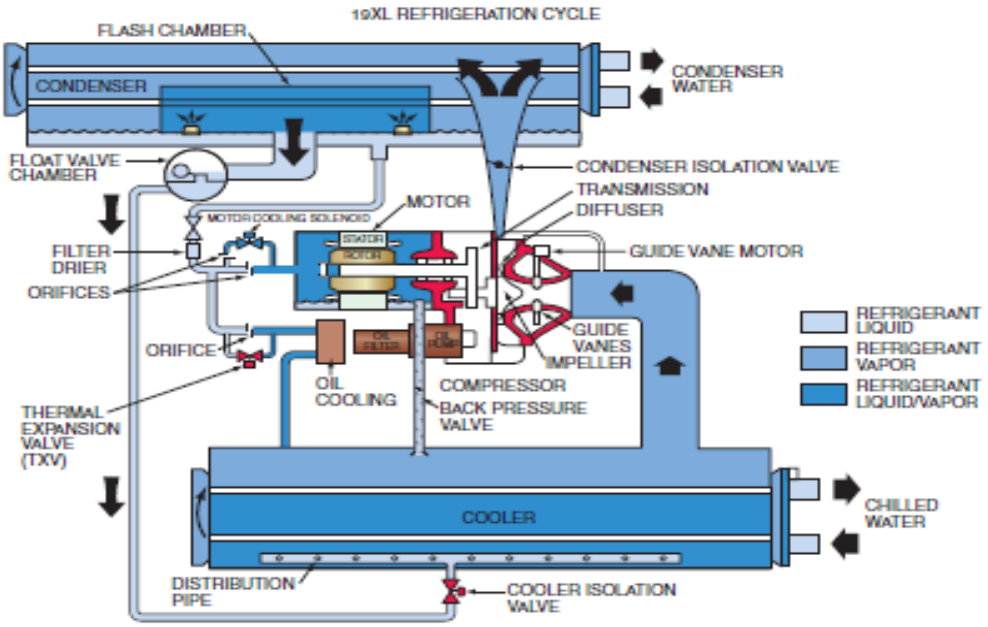
Fig. 1 ASHRAE Psychrometric Chart No. 1

الجامعة التقنية الجنوبية
المعهد التقني / بصرة
قسم تقنيات ميكانيك القدرة
فرع التبريد والتكييف

مبادئ التبريد

المرحلة الاولى

Principles of Refrigeration



Unit 1

Principles of refrigeration

Heat transfer :

Heat is energy in the form of molecules in motion. As a substance becomes warmer, its molecular motion and energy level (temperature) increases. Temperature describes the level of heat (energy) with reference to no heat.

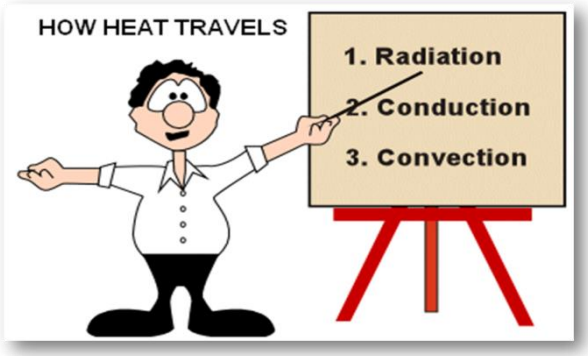
Heat naturally flows from a higher energy level to a lower energy level. In other words, heat travels from a warmer substance to a cooler substance. When there is a temperature difference between two substances, heat transfer will occur.

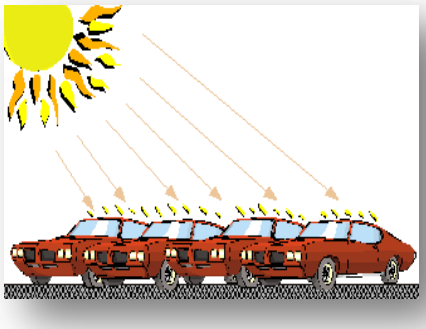
In fact, temperature difference is the driving force behind heat transfer. The greater the temperature difference, the greater the heat transfer.

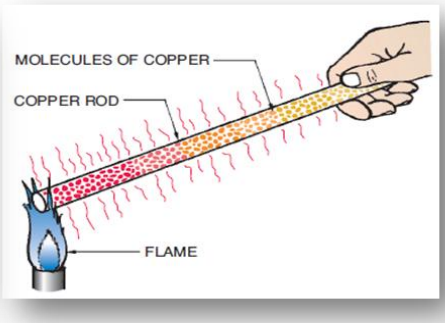
Types of Heat Transfer :

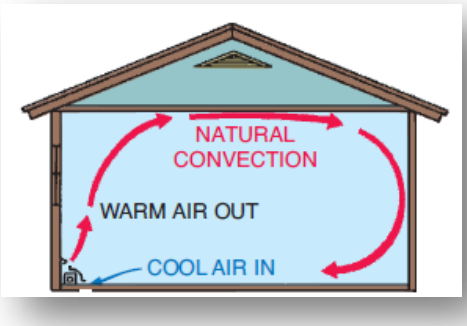
The science that deals with the determination of the rates of such energy transfers is **heat transfer.**

Heat can be transferred in three different modes: **conduction, convection**, and **radiation**. All modes of heat transfer require the existence of a temperature difference, and all modes are from the high-temperature medium to a lower-temperature one.





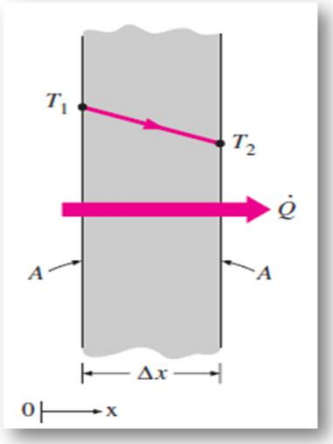




Conduction :

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion. In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.
The rate of heat conduction through a medium depends on the geometry of the medium, its thickness, and the material of the medium, as well as the temperature difference across the medium.

Consider steady heat conduction through a large plane wall of thickness △x = L and area A, as shown in the Figure.



The temperature difference across the wall is **△T = T_2 - T_1**. Experiments have shown that the rate of heat transfer **Q** through the wall is doubled when the temperature difference **△T** across the wall or the area A normal to the direction of heat transfer is doubled, but is halved when the wall thickness **L** is doubled. Thus we conclude that the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad \text{(W)}$$

where the constant of proportionality **k** is the thermal conductivity of the material, which is a measure of the ability of a material to conduct heat . In the limiting case of x →0, the equation above reduces to the differential form, which is called **Fourier's law** of heat conduction after J. Fourier, who expressed it first in his heat transfer text in 1822.

$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx} \qquad \text{(W)}$$

Here dT/dx is the temperature gradient, which is the slope of the temperature curve on a T-x diagram (the rate of change of T with x), at location x. The previous relation indicates that the rate of heat conduction in a direction is proportional to the temperature gradient in that direction. Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing x.

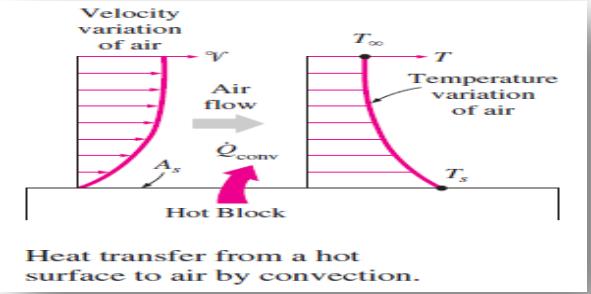
The '-' sign in the previous equation is a consequence of second law of thermodynamics, which states that in spontaneous process heat must always flow from a high temperature to a low temperature (i.e., dT/dx must be negative). The heat transfer area A is always normal to the direction of heat transfer.

Convection :

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion. The faster the fluid motion, the greater the convection heat transfer.

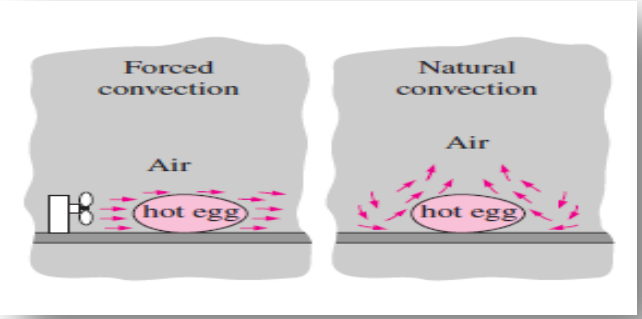
In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

Consider the cooling of a hot block by blowing cool air over its top surface (Figure below). Energy is first transferred to the air layer adjacent to the block by conduction. This energy is then carried away from the surface by convection, that is, by the combined effects of conduction within the air that is due to random motion of air molecules and the bulk or macroscopic motion of the air that removes the heated air near the surface and replaces it by the cooler air.



Heat transfer from a hot surface to air by convection.

Convection is called **forced convection** if the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind. In contrast, convection is called **natural (or free) convection** if the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid (Figure below).



For example, in the absence of a fan, heat transfer from the surface of the hot body will be by natural convection since any motion in the air in this case will be due to the rise of the warmer (and thus lighter) air near the surface and the fall of the cooler (and thus heavier) air to fill its place. Heat transfer between the body and the surrounding air will be by conduction if the temperature difference between the air and the body is not large enough to overcome the resistance of air to movement and thus to initiate natural convection currents.

Heat transfer processes that involve change of phase of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

Despite the complexity of convection, the rate of convection heat transfer is observed to be proportional to the temperature difference, and is conveniently expressed by Newton's law of cooling as:

$$\dot{Q}_{\text{conv}} = hA_s\,(T_s - T_\infty) \qquad \text{(W)}$$

Where **h** is the **convection heat transfer coefficient** in $W/m^2 \cdot {}^\circ C$ or $Btu/h \cdot ft^2 \cdot {}^\circ F$, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far from the surface. Note that at the surface, the fluid temperature equals the surface temperature of the solid.

The convection heat transfer coefficient **h** is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity

Radiation :

Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium. In fact, energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.

In heat transfer studies we are interested in thermal radiation, which is the form of radiation emitted by bodies because of their temperature. It differs from other forms of electromagnetic radiation such as x-rays, gamma rays, microwaves, radio waves, and television waves that are not related to temperature. All bodies at a temperature above absolute zero emit thermal radiation. Radiation is a volumetric phenomenon, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.

However, radiation is usually considered to be a surface phenomenon for solids that are opaque to thermal radiation such as metals, wood, and rocks since the radiation emitted by the interior regions of such material can never reach the surface, and the radiation incident on such bodies is usually absorbed within a few microns from the surface.

The maximum rate of radiation that can be emitted from a surface at an absolute temperature Ts (in K or °R) is given by the **Stefan–Boltzmann law** as

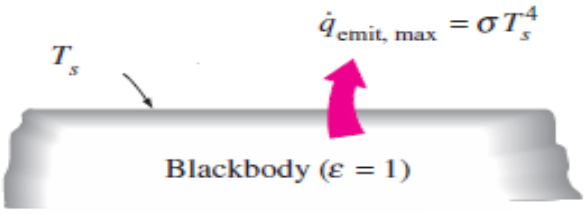
$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \qquad \text{(W)}$$

Where $\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$ or $0.1714 \times 10^{-8}\ \text{Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$ is the Stefan–Boltzmann constant.

The idealized surface that emits radiation at this maximum rate is called a **blackbody**, and the radiation emitted by a blackbody is called blackbody radiation (Figure below). The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as:

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{(W)}$$

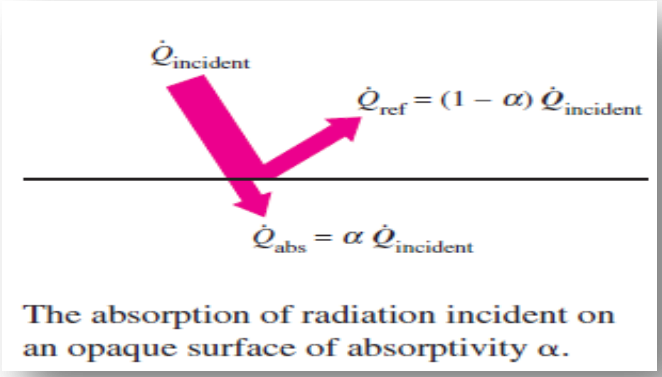
where ε is the **emissivity** of the surface. The property emissivity, whose value is in the range **$0 \le \varepsilon \le 1$**, is a measure of how closely a surface approximates a **blackbody** for which $\varepsilon = 1$.



Blackbody radiation represents the *maximum amount of radiation that can be emitted from a surface at a specified temperature.*

Another important radiation property of a surface is its **absorptivity (α),** which is the fraction of the radiation energy incident on a surface that is absorbed by the surface. Like emissivity, its value is in the range **$0 \le \alpha \le 1$.**

A blackbody absorbs the entire radiation incident on it. That is, a blackbody is a perfect absorber (α=1) as it is a perfect emitter.



The absorption of radiation incident on an opaque surface of absorptivity α.

In general, both ε and α of a surface depend on the temperature and the wavelength of the radiation. **Kirchhoff's law** of radiation states that the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal. In many practical applications, the surface temperature and the temperature of the source of incident radiation are of the same order of magnitude, and the average absorptivity of a surface is taken to be equal to its average emissivity.

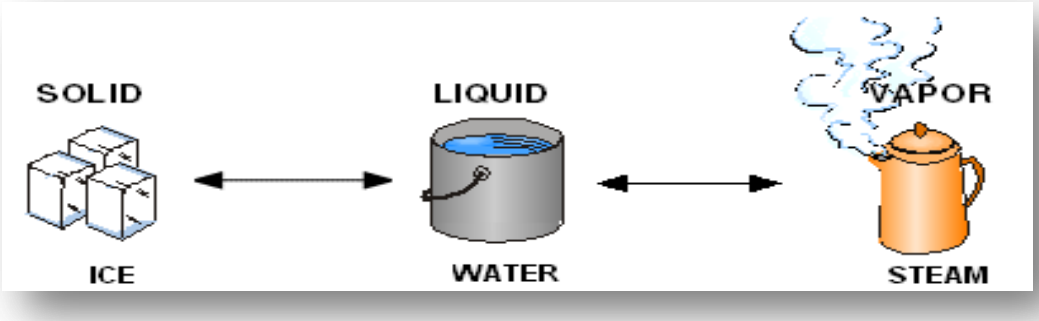
$$\dot{Q}_{absorbed} = \alpha \dot{Q}_{incident} \qquad (W)$$

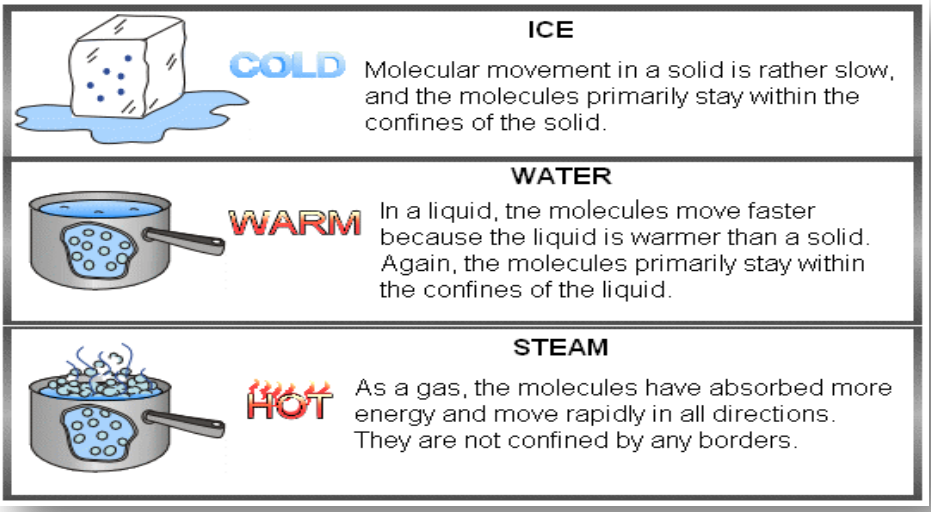
where $\dot{Q}_{incident}$ is the rate at which radiation is incident on the surface and α is the absorptivity of the surface. For opaque (nontransparent) surfaces, the portion of incident radiation not absorbed by the surface is reflected back.

The difference between the rates of radiation emitted by the surface and the radiation absorbed is the net radiation heat transfer.

Physical States of Matter :

Most substances can exist in three physical states, **solid**, **liquid** ,or **gas**. As heat is added or removed, the substance will change temperature, or physical state. When a substance changes from one physical state to another, the temperature does not change until all the molecules are arranged to the new physical state. The same amount of heat are required whether adding or removing heat.



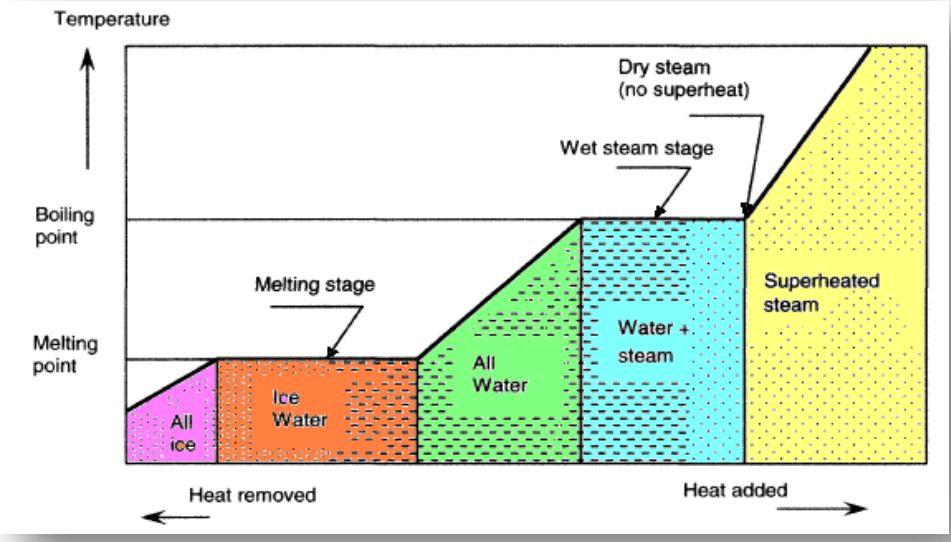


State and Change of State :

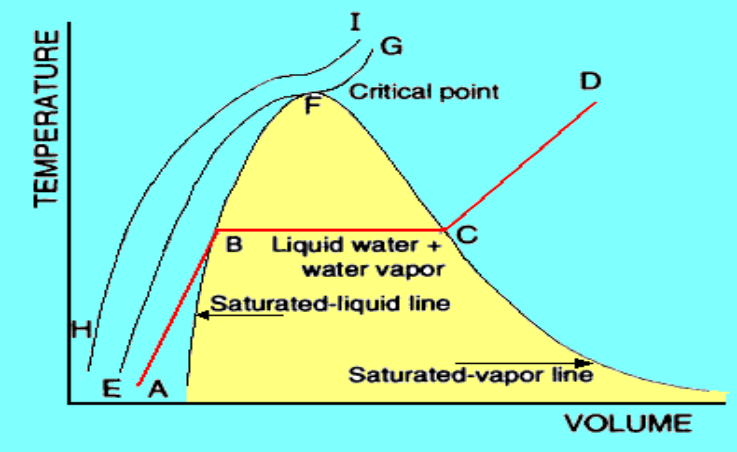
The state of a system or substance is defined as the condition of the system or substance characterized by the certain observable macroscopic values of its properties such as temperature and pressure. The term **state** is often used interchangeably with the term **phase**, e.g. solid phase or gaseous phase of a substance. Each of the properties of a substance in a given state has only one definite value, regardless of how the substance reached the state.

For example, when sufficient heat is added or removed, most substances undergo a state change. The temperature remains constant until the state change is complete. This can be from solid to liquid, liquid to vapor, or vice versa. Next figure shows the typical examples of ice melting and water boiling.

The State-Change Diagram of Water :



A clearer presentation of solid, liquid, and vapor phases of water is exhibited on a temperature-volume (T-v) diagram in figure below. The constant pressure line ABCD represents the states which water passes through as follows:



A-B: This represents the process where water is heated from the initial temperature to the saturation temperature (liquid) at constant pressure. At point B it is fully saturated liquid water with a quality

x = 0, with zero quantity of water vapor.

B-C: This is the constant-temperature vaporization process in which there is only phase change from saturated liquid to saturated vapor, referring to the fact that the quality varies from 0 to 100%. Within this zone, the water is a mixture of liquid water and water vapor. At point C it is completely saturated vapor and the quality is 100%.

C-D: This represents the constant-pressure process in which the saturated water vapor is superheated with increasing temperature.

E-F-G: In this line there is no constant-temperature vaporization process. The point F is called the critical point where the saturated-liquid and saturated-vapor states are identical. The thermodynamic properties at this point are called critical thermodynamic properties, e.g. critical temperature, critical pressure, and critical specific volume.

H-I: This is a constant-pressure heating process in which there is no phase change from one phase to another (one is present only); however, there is a continuous change in density.

Critical Point :

A liquid below the critical pressure when heated first becomes a mixture of liquid and vapour and then becomes saturated vapour and finally a superheated vapour.

At critical point there is no distinction between liquid state and vapour state; these two merge together. At constant pressure greater than critical pressure, when liquid is heated in supercritical region, there is no distinction between liquid and vapour; as a result if

heating is done in a transparent tube, the meniscus of liquid and vapour does not appear as transformation from liquid to vapour takes place.

At pressures below critical pressure, when a liquid is heated there is a clear-cut meniscus between liquid and vapour, until all the liquid evaporates.

Critical Temperature:

The critical temperature of a substance is the highest temperature at which the substance may be liquefied, regardless of pressure applied upon it.

The condensing temperatures for a refrigerant must be kept below its critical temperature, otherwise, the refrigerant will not operate. Carbon dioxide (R-744) has an critical temperature of (31 °C). This refrigerant is not used in air-cooled compression systems. This is because the condensing temperature would usually be above this temperature.

Critical Pressure:

The critical pressure of a substance is the minimum pressure necessary to liquefy a gas that is at its critical temperature. Less pressure will not liquefy it.

Unit 1 Questions

Q1: Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. radiation b. blackbody c. thermal conductivity d. temperature e. absolute zero

1. All modes of heat transfer require the existence of a _____ difference.
2. The constant of proportionality for conduction heat transfer is the _____ of the material.
3. The transfer of energy by _____ does not require the presence of an intervening medium.
4. All bodies at a temperature above _____ emit thermal radiation.
5. The idealized surface that emits radiation at this maximum rate is called a _____ .

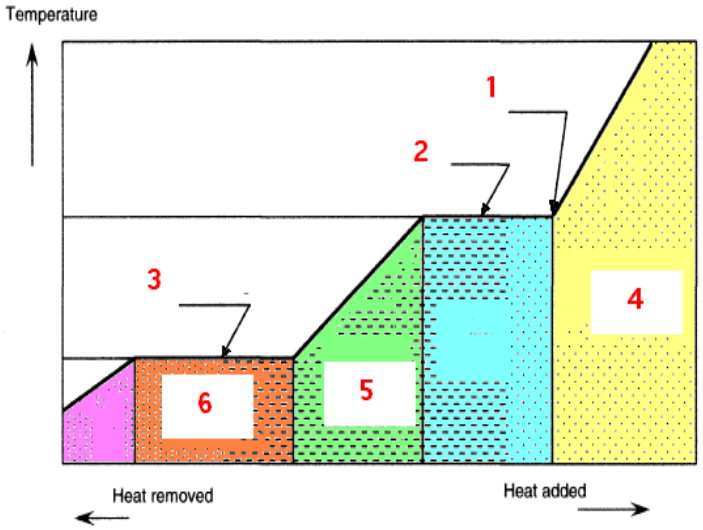
Q2: Answer the following questions.

1. What are three methods of heat transfer?
2. Name two types of convection?
3. Name three physical states of matter?
4. What is the constant of proportionality in Fourier's law of heat conduction ?
5. What Kirchhoff's law of radiation states?
6. What is the value of the emissivity (ε) of a surface?

Q3: Identify the points in the diagram shown below. Select your answers from the list, then print the letters in the appropriate blanks.

1. _____
2. _____
3. _____
4. _____
5. _____
6. _____

a. Superheated steam
b. Melting stage
c. Wet steam stage
d. Ice water
e. Dry steam
f. All water



References:

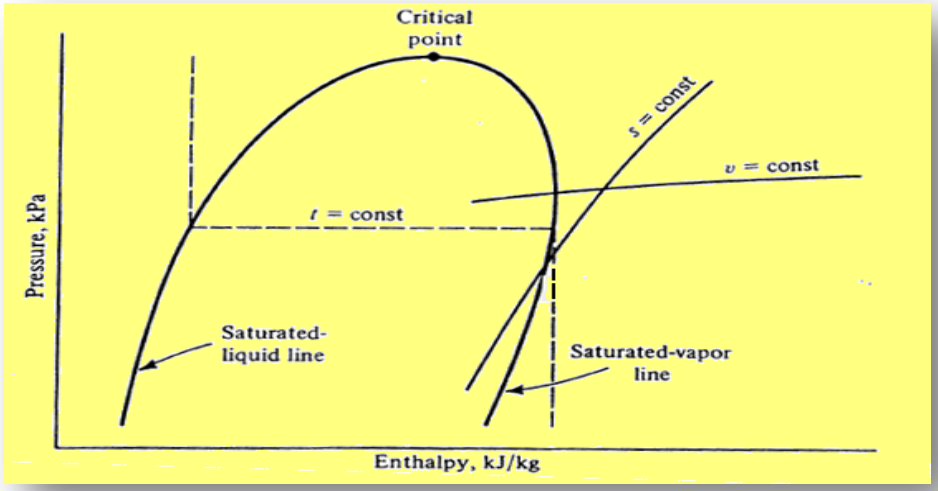
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2. Jerry, LaDonaa Killinger, Lessons in Air Conditioning and Refrigeration, GW Publisher, 2000.
3. Bill Whitman, Bill Johnson, John Tomczyk, Eugene Silberstein, Refrigeration and Air conditioning Technology, Sixth Edition, Delmar, Cengage Learning, 2009.
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Unit 2

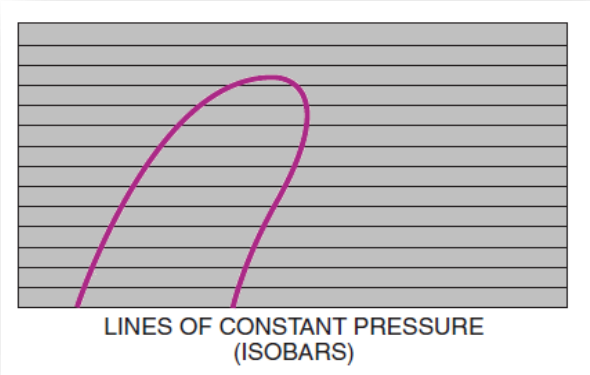
P-h Diagram

Pressure/Enthalpy (P-h) Diagram:

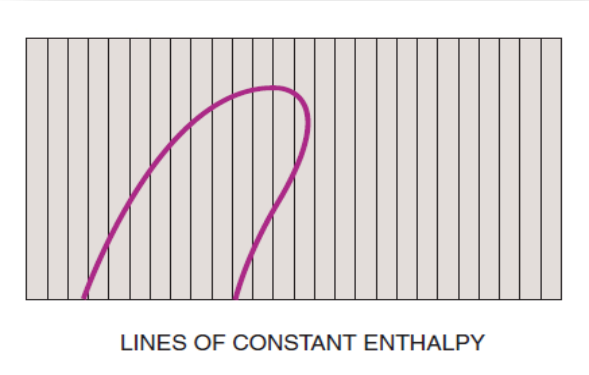
A skeleton pressure-enthalpy diagram is shown in the figure below. The pressure is the ordinate and the enthalpy the abscissa. With the saturated - vapour and saturated-liquid lines as the reference, lines of constant temperature, entropy, and specific volume appear on the diagram



The pressure/enthalpy diagram is a similar diagram, is available for all refrigerants, and is sometimes referred to as a p-e (pressure/enthalpy) or p-h (pressure/heat) chart. Since different refrigerants have different characteristics, properties, and temperature/pressure relationships, the pressure/enthalpy diagram for each refrigerant is different. The pressure/enthalpy chart is used to plot the complete refrigeration cycle as a continuous loop.



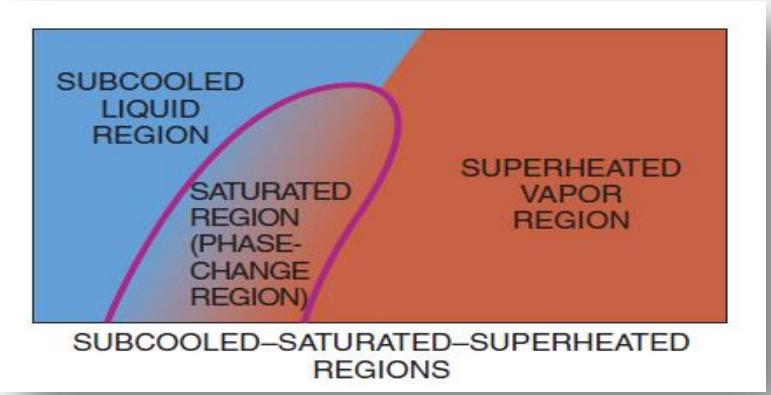
LINES OF CONSTANT PRESSURE (ISOBARS)



LINES OF CONSTANT ENTHALPY

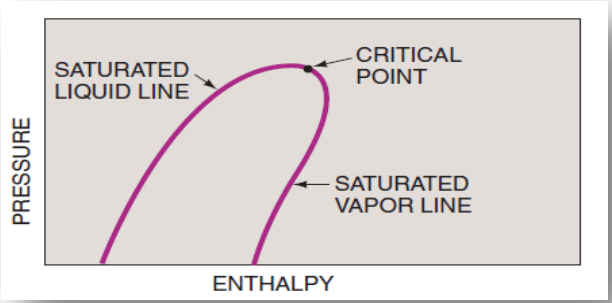
As you inspect the pressure/enthalpy diagram in figure below, you will notice that there is a horseshoe-shaped curve toward the center of the chart. This curve is called the saturation curve. Any time a plot falls on, or under, this curve, the refrigerant is saturated and will have a corresponding temperature and pressure relationship.

The three major regions on the diagram are (1) the sub-cooled- liquid region to the left,(2) the liquid-vapour region in the centre, and (3) the superheated-vapour region on the right.



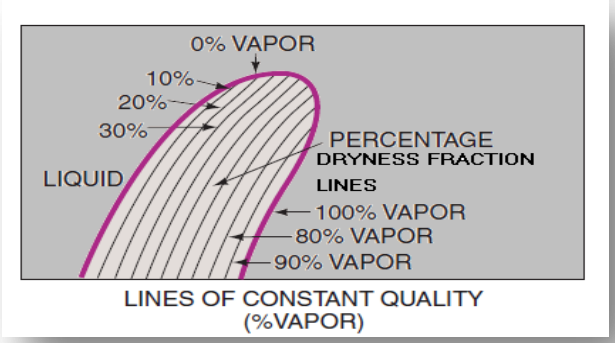
SUBCOOLED–SATURATED–SUPERHEATED REGIONS

Two saturation curves exist; the one on the left is the saturated liquid curve. If heat is added, the refrigerant will start changing state to a vapour. If heat is removed, the liquid will be sub-cooled. The right-hand curve is the saturated vapour curve. If heat is added, the vapour will superheat. If heat is removed, the vapour will start changing state to a liquid. Notice that the saturated liquid and vapour curves touch at the top. This is called the critical point. Above this point, the refrigerant will not condense. It is a vapour regardless of how much pressure is applied**.**



The area between the saturated liquid and saturated vapour curve, inside the horseshoe-shaped curve, is where the change of state occurs. Any time a plot falls between the saturation curves, the refrigerant is in the partial liquid, partial vapour state.

The slanted, near-vertical lines between the saturated liquid and saturated vapor lines are the dryness fraction lines and describe the percentage of vapour to liquid in the mixture between the saturation points. There are nine of these lines.



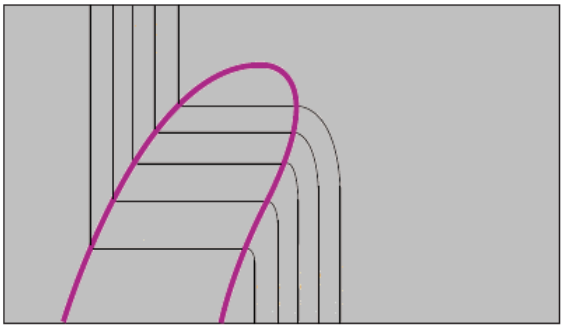
LINES OF CONSTANT QUALITY (%VAPOR)

Under the saturation curve and each of these lines represents 10%. The saturated liquid line on the left side of the curve represents 0% vapour and 100% liquid, while the saturated vapour line on the right side of the saturation curve represents 100% vapour and 0% liquid. The nine constant quality (dryness fraction) lines that are located under the saturation curve are labeled, from left to right, 10 through 90. These numbers represent the percentage of quality (dryness fraction). Percentage of quality means percentage of vapour. This means that if a point falls on the 20% constant quality line, it would be 20% vapour and 80% liquid. If the plot is closer to the saturated liquid curve, there is more liquid than vapor. If the plot is closer to the saturated vapour curve, there is more vapour than liquid.

On the left-hand side of the saturation curve, practically, the lines of constant temperature (isotherms) are vertically downward until they intersect the saturated liquid curve.

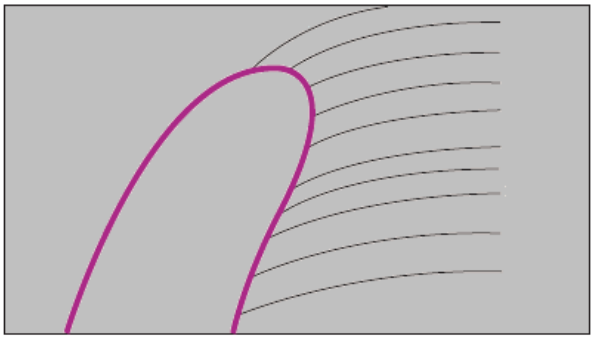
The lines are horizontal, as they travel from saturated liquid to saturated vapour.

In the superheat region the lines of constant temperature drops first slightly to the right and then vertically.

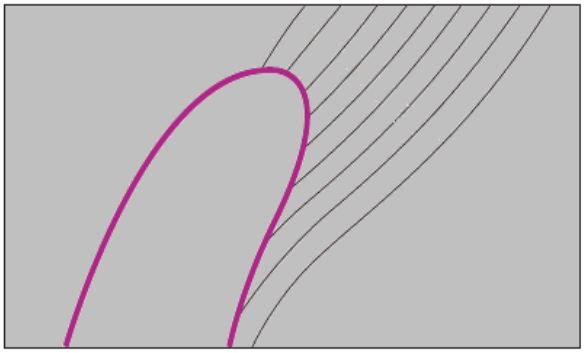


LINES OF CONSTANT TEMP.
(ISOTHERMS)

On the right-hand side of the saturation curve, the lines of constant specific volume slopes upward to the right. Lines of higher specific volumes are found at progressively lower pressure. The lines of constant entropy (isentropic) runs upward to the right.

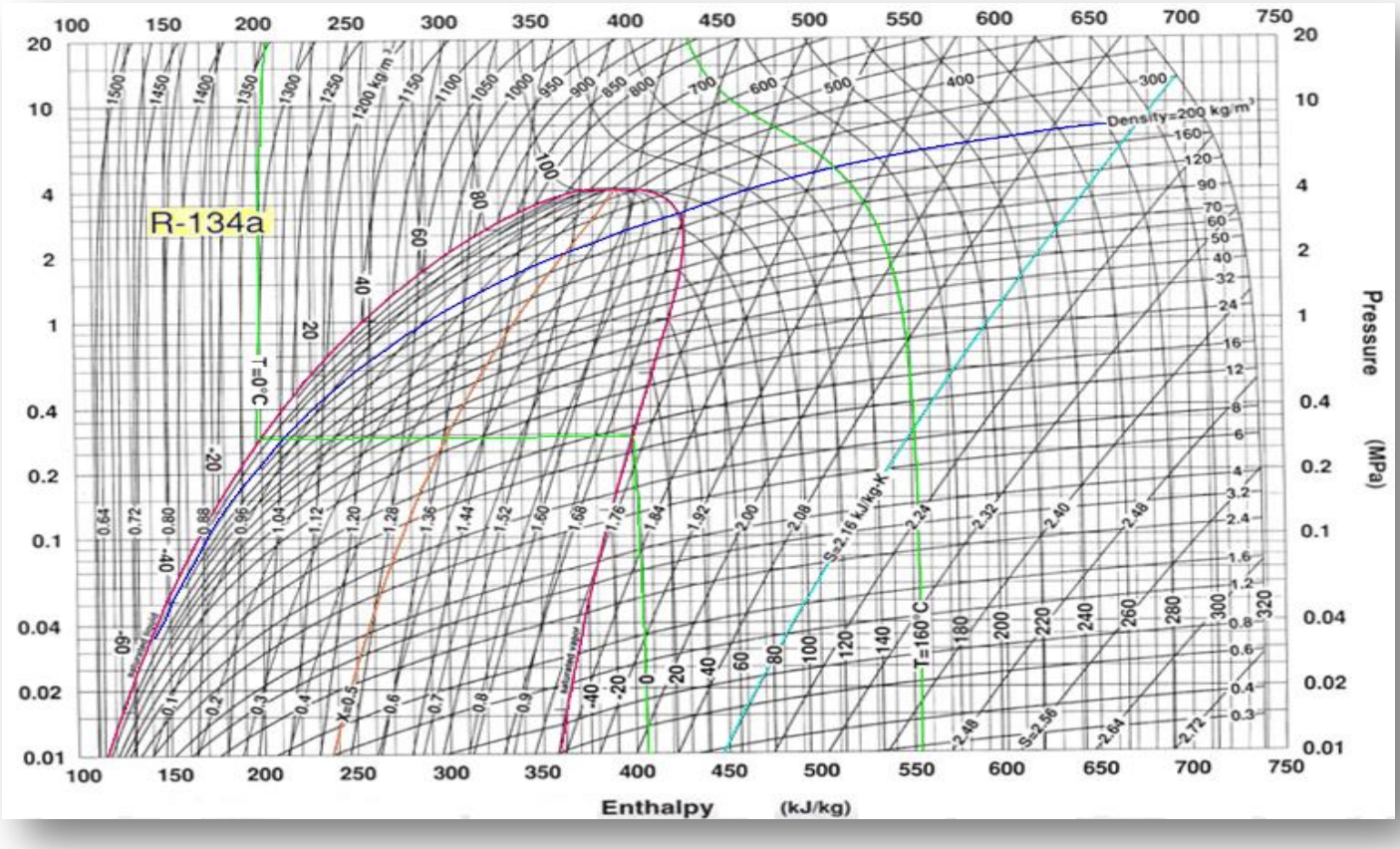


LINES OF CONSTANT SPECIFIC VOLUME



LINES OF CONSTANT ENTROPY

P-h Diagram for R-134a



Saturation Properties for R-134a

HFC–134a Saturation Properties—Temperature Table

TEMP. °C	PRESSURE kPa (abs)	VOLUME m³/kg LIQUID v_f	VOLUME m³/kg VAPOR v_g	DENSITY kg/m³ LIQUID $1/v_f$	DENSITY kg/m³ VAPOR $1/v_g$	ENTHALPY kJ/kg LIQUID h_f	ENTHALPY kJ/kg LATENT h_{fg}	ENTHALPY kJ/kg VAPOR h_g	ENTROPY kJ/(kg)(K) LIQUID s_f	ENTROPY kJ/(kg)(K) VAPOR s_g
−40	51.14	0.0007	0.3614	1414.6	2.767	148.4	225.9	374.3	0.7967	1.7655
−39	53.88	0.0007	0.3441	1411.8	2.906	149.6	225.3	374.9	0.8020	1.7641
−38	56.74	0.0007	0.3279	1408.9	3.050	150.9	224.7	375.5	0.8073	1.7627
−37	59.72	0.0007	0.3125	1406.0	3.200	152.1	224.0	376.2	0.8126	1.7613
−36	62.83	0.0007	0.2980	1403.1	3.356	153.4	223.4	376.8	0.8178	1.7599
−35	66.07	0.0007	0.2843	1400.2	3.518	154.6	222.8	377.4	0.8231	1.7586
−34	69.43	0.0007	0.2713	1397.4	3.686	155.9	222.2	378.1	0.8283	1.7573
−33	72.93	0.0007	0.2590	1394.5	3.861	157.1	221.5	378.7	0.8336	1.7561
−32	76.58	0.0007	0.2474	1391.5	4.042	158.4	220.9	379.3	0.8388	1.7548
−31	80.36	0.0007	0.2365	1388.6	4.229	159.7	220.3	379.9	0.8440	1.7536
−30	84.29	0.0007	0.2260	1385.7	4.424	160.9	219.6	380.6	0.8492	1.7525
−29	88.37	0.0007	0.2162	1382.8	4.625	162.2	219.0	381.2	0.8544	1.7513
−28	92.61	0.0007	0.2069	1379.8	4.833	163.5	218.3	381.8	0.8595	1.7502
−27	97.02	0.0007	0.1981	1376.9	5.049	164.7	217.7	382.4	0.8647	1.7491
−26	101.58	0.0007	0.1896	1373.9	5.273	166.0	217.1	383.1	0.8698	1.7481
−25	106.32	0.0007	0.1817	1371.0	5.504	167.3	216.4	383.7	0.8750	1.747
−24	111.22	0.0007	0.1741	1368.0	5.743	168.6	215.7	384.3	0.8801	1.746
−23	116.31	0.0007	0.1669	1365.0	5.991	169.8	215.1	384.9	0.8852	1.745
−22	121.57	0.0007	0.1601	1362.0	6.247	171.1	214.4	385.5	0.8903	1.744
−21	127.02	0.0007	0.1536	1359.0	6.511	172.4	213.7	386.2	0.8954	1.7431

TEMP. °C	PRESSURE kPa (abs)	VOLUME m³/kg LIQUID v_f	VOLUME m³/kg VAPOR v_g	DENSITY kg/m³ LIQUID $1/v_f$	DENSITY kg/m³ VAPOR $1/v_g$	ENTHALPY kJ/kg LIQUID h_f	ENTHALPY kJ/kg LATENT h_{fg}	ENTHALPY kJ/kg VAPOR h_g	ENTROPY kJ/(kg)(K) LIQUID s_f	ENTROPY kJ/(kg)(K) VAPOR s_g
20	572.25	0.0008	0.0360	1224.4	27.791	227.5	182.5	410.0	1.0964	1.7189
21	590.16	0.0008	0.0349	1220.7	28.659	228.9	181.6	410.5	1.1012	1.7185
22	608.49	0.0008	0.0338	1217.0	29.549	230.4	180.7	411.0	1.1060	1.7182
23	627.25	0.0008	0.0328	1213.3	30.462	231.8	179.8	411.6	1.1107	1.7178
24	646.44	0.0008	0.0318	1209.6	31.399	233.2	178.9	412.1	1.1155	1.7175
25	666.06	0.0008	0.0309	1205.9	32.359	234.6	178.0	412.6	1.1202	1.7171
26	686.13	0.0008	0.0300	1202.1	33.344	236.1	177.0	413.1	1.1250	1.7168
27	706.66	0.0008	0.0291	1198.3	34.354	237.5	176.1	413.6	1.1297	1.7165
28	727.64	0.0008	0.0283	1194.4	35.389	238.9	175.2	414.1	1.1345	1.7161
29	749.04	0.0008	0.0274	1190.6	36.451	240.4	174.2	414.6	1.1392	1.7158
30	771.02	0.0008	0.0266	1186.7	37.540	241.8	173.3	415.1	1.1439	1.7155
31	793.43	0.0008	0.0259	1182.8	38.657	43.3	172.3	415.6	1.1487	1.7151
32	816.28	0.0008	0.0251	1178.8	39.802	44.8	171.3	416.1	1.1534	1.7148
33	839.66	0.0009	0.0244	1174.9	40.975	246.2	170.3	416.6	1.1581	1.7145
34	863.53	0.0009	0.0237	1170.8	42.179	247.7	169.3	417.0	1.1628	1.7142
35	887.91	0.0009	0.0230	1166.8	43.413	249.2	168.3	417.5	1.1676	1.7138
36	912.80	0.0009	0.0224	1162.7	44.679	250.6	167.3	418.0	1.1723	1.7135
37	938.20	0.0009	0.0218	1158.6	45.977	252.1	166.3	418.4	1.1770	1.7132
38	964.14	0.0009	0.0211	1154.5	47.308	253.6	165.3	418.9	1.1817	1.7129
39	990.60	0.0009	0.0205	1150.3	48.672	255.1	164.2	419.3	1.1864	1.7125

Unit 2 Questions

Q1: Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. critical point **b**. dryness fraction **c**. pressure **d**. superheated vapour **e**. enthalpy

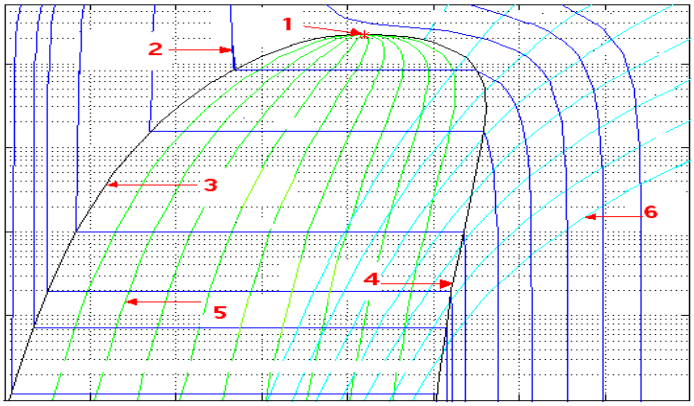
1. P-h diagram plots _____on the left-hand side of the diagram and _____ on the bottom .
2. The saturated liquid and vapour curves touch at the top. This is called the _____.
3. On the right-hand side of the saturation curve is _____ region.
4. _____lines describe the percentage of vapour to liquid in the mixture.

Q2: What are the values of the following properties for **R-134a** saturated vapour at **20 °C** ? (use the saturation tables and P-h diagram and compare the results).

1. Enthalpy
2. Entropy
3. Specific volume
4. Pressure
5. Dryness fraction

Q3: Identify the points in the diagram shown below. Select your answers from the list, then print the letters in the appropriate blanks.

1. _____ a. Saturated vapour
2. _____ b. Constant entropy line
3. _____ c. Dryness fraction line
4. _____ d. Critical point
5. _____ e Constant temperature line
6. _____ f. Saturated liquid



References:

1. Bill Whitman, Bill Johnson, John Tomczyk, Eugene Silberstein, Refrigeration and Air conditioning Technology, Sixth Edition, Delmar, Cengage Learning, 2009.

2. W. F. Stoecker, W.P. Jones, Refrigeration and air conditioning, Second Edition, McGraw-Hill.

Unit 3

Vapour compression systems

vapour compression refrigeration systems are the most commonly used among all refrigeration systems. As the name implies, these systems belong to the general class of vapour cycles, wherein the working fluid (**refrigerant**) undergoes phase change at least during one process.

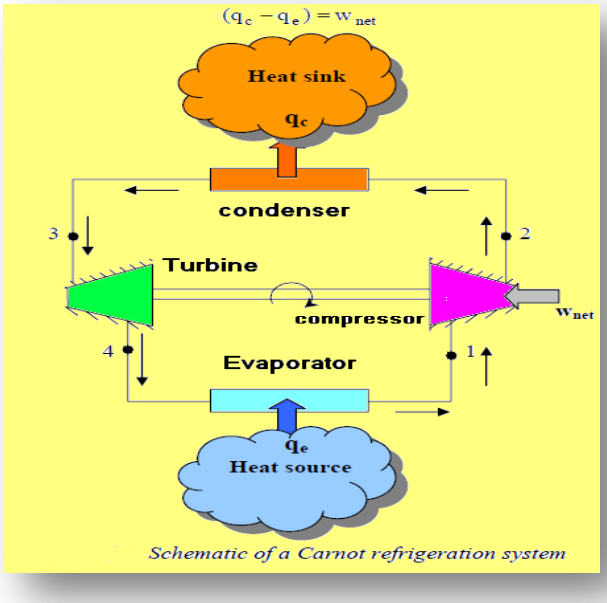
In a vapour compression refrigeration system, refrigeration is obtained as the refrigerant evaporates at low temperatures. The input to the system is in the form of mechanical energy required to run the compressor. Hence these systems are also called as mechanical refrigeration systems.

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

The Carnot Refrigeration Cycle

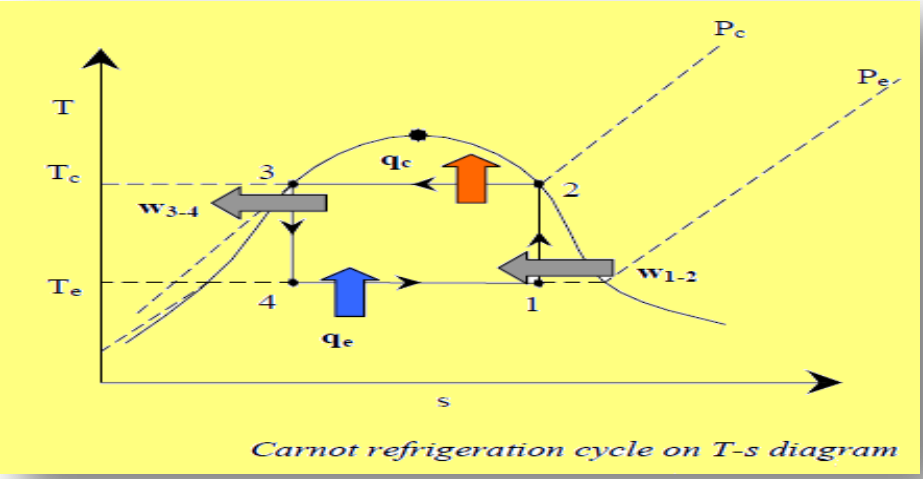
Carnot refrigeration cycle is a completely reversible cycle, hence is used as a model of perfection for a refrigeration cycle operating between a constant temperature heat source and sink. It is used as reference against which the real cycles are compared.

As shown in the figure, the basic Carnot refrigeration system for pure vapour consists of four components: **compressor**, **condenser**, **turbine** and **evaporator**.



Schematic of a Carnot refrigeration system

Refrigeration effect ($q_{4-1} = q_e$) is obtained at the evaporator as the refrigerant undergoes the process of vaporization (process 4-1) and extracts the latent heat from the low temperature heat source. The low temperature, low pressure vapour is then compressed isentropically in the compressor to the heat sink temperature T_c. The refrigerant pressure increases from P_e to P_c during the compression process (process 1-2) and the exit vapour is saturated. Next the high pressure, high temperature saturated refrigerant undergoes the process of condensation in the condenser (process 2-3) as it rejects the heat of condensation ($q_{2-3} = q_c$) to an external heat sink at T_c.



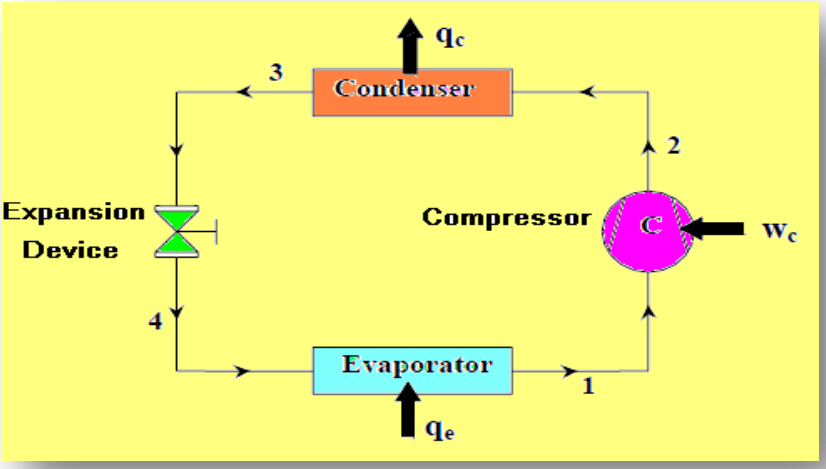
Carnot refrigeration cycle on T-s diagram

The high pressure saturated liquid then flows through the turbine and undergoes isentropic expansion (process 3-4). During this process, the pressure and temperature fall from P_C,T_C to P_e,T_e. Since a saturated liquid is expanded in the turbine, some amount of liquid flashes into vapour and the exit condition lies in the two-phase region. This low temperature and low pressure liquid-vapour mixture then enters the evaporator completing the cycle.

From practical considerations, the Carnot refrigeration system need to be modified. Dry compression with a single compressor is possible if the isothermal heat rejection process is replaced by isobaric heat rejection process. Similarly, the isentropic expansion process can be replaced by an isenthalpic throttling process. A refrigeration system, which incorporates these two changes is known as Evans-Perkins or reverse Rankine cycle. This is the theoretical cycle on which the actual vapour compression refrigeration systems are based.

Standard Vapour Compression Refrigeration System

Figure shows the schematic of a standard, saturated, single stage vapour compression refrigeration system . This system consists of the following four processes:

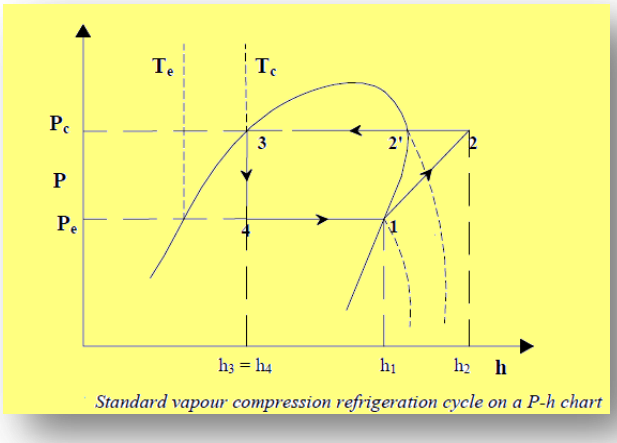


Process 1-2: Isentropic compression of saturated vapour in compressor

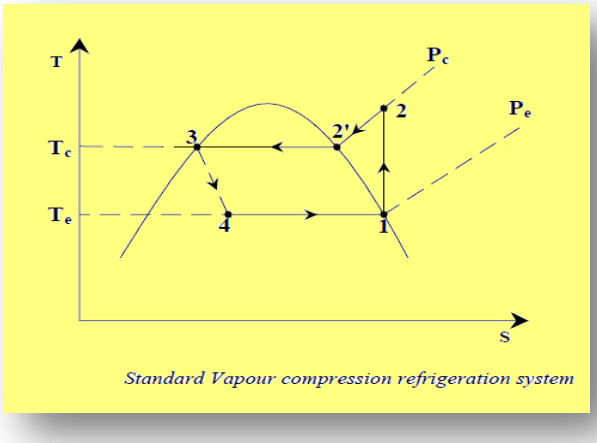
Process 2-3: Isobaric heat rejection in condenser

Process 3-4: Isenthalpic expansion of saturated liquid in expansion device

Process 4-1: Isobaric heat extraction in the evaporator



Standard vapour compression refrigeration cycle on a P-h chart



Standard Vapour compression refrigeration system

Analysis of Standard Vapour Compression Refrigeration System

A simple analysis of standard vapour compression refrigeration system can be carried out by assuming (a) Steady flow; (b) negligible kinetic and potential energy changes across each component, and (c) no heat transfer in connecting pipe lines. The steady flow energy equation is applied to each of the four components.

Evaporator: Heat transfer rate at evaporator or refrigeration capacity, is given by:

$$Q_e = m_r (h_1 - h_4)$$

where m_r is the refrigerant mass flow rate in kg/s, h_1 and h_4 are the specific enthalpies (kJ/kg) at the exit and inlet to the evaporator, respectively.

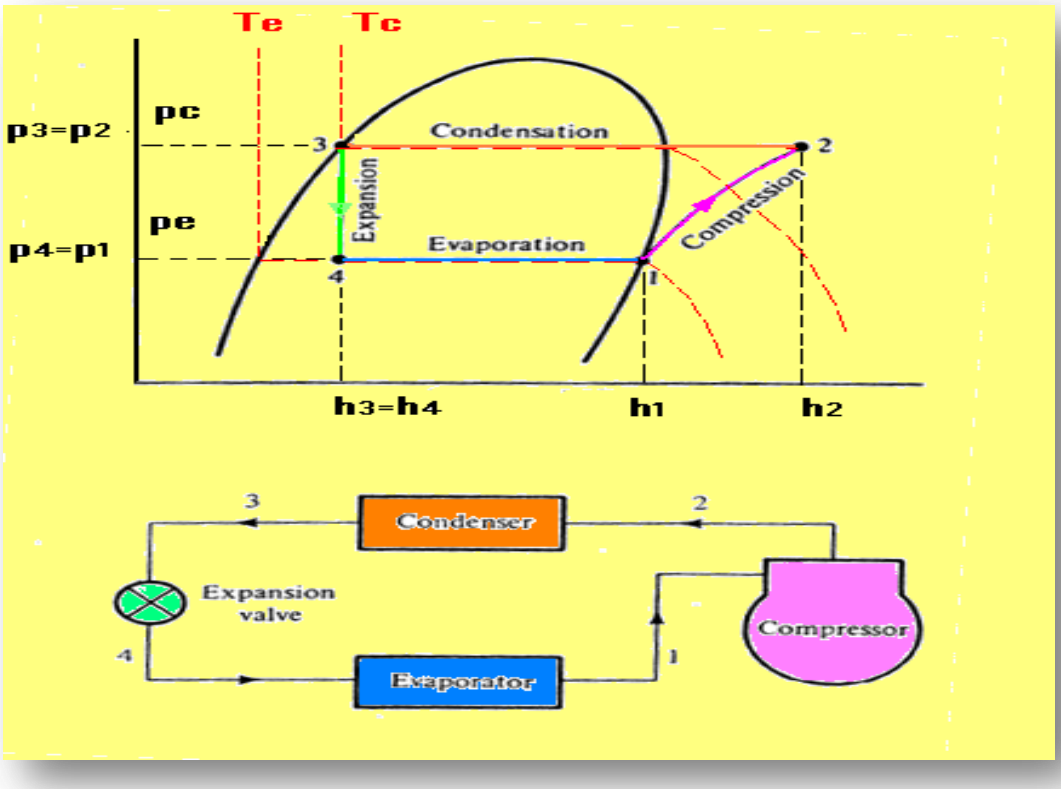
$(h_1 - h_4)$ is known as specific refrigeration effect or simply **refrigeration effect**, which is equal to the heat transferred at the evaporator per kilogram of refrigerant. The evaporator pressure P_e is the saturation pressure corresponding to evaporator temperature T_e.

Compressor: Power input to the compressor, W_c is given by:

$$W_c = m_r (h_2 - h_1)$$

Where h_2 and h_1 are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor, respectively.

($h_2 - h_1$) is known as specific work of compression or simply **work of compression**, which is equal to the work input to the compressor per kilogram of refrigerant.



Condenser: Heat transfer rate at condenser, Qc is given by:

$$Q_c = m_r (h_2 - h_3)$$

where h_3 and h_2 are the specific enthalpies (kJ/kg) at the exit and inlet to the condenser, respectively. The condenser pressure P_c is the saturation pressure corresponding to evaporator temperature T_c .

Expansion device: For the isenthalpic expansion across the expansion device could be considerable, however, if we take the control process, the kinetic energy change volume, well downstream of the expansion device, then the kinetic energy gets dissipated due to viscous effects, and $h_3 = h_4$

The exit condition of the expansion device lies in the two-phase region, hence applying the definition of quality (or **dryness fraction**), we can write:

$$h_4 = (1 - X_4)\, h_{f,e} + X_4\, h_{g,e} = h_f + X_4\, h_{fg}$$

where X_4 is the dryness fraction of refrigerant at point 4, $h_{f,e}$, $h_{g,e}$, h_{fg} are the saturated liquid enthalpy, saturated vapour enthalpy and latent heat of vaporization at evaporator pressure, respectively.

The **Coefficient of Performance (COP)** of the system is given by:

$$\mathbf{COP} = \frac{\text{refrigeration effect}}{\text{net work input}}$$

$$COP = \left(\frac{\dot{Q}_e}{\dot{W}_c} \right) = \left(\frac{\dot{m}_r (h_1 - h_4)}{\dot{m}_r (h_2 - h_1)} \right) = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$

Generally, the type of refrigerant, required refrigeration capacity, evaporator temperature and condenser temperature are known. Then from the evaporator and condenser

temperature one can find the evaporator and condenser pressures and enthalpies at the exit of evaporator and condenser (saturated vapour enthalpy at evaporator pressure and saturated liquid enthalpy at condenser pressure).

Since the exit condition of the compressor is in the superheated region, two independent properties are required to fix the state of refrigerant at this point. One of these independent properties could be the condenser pressure, which is already known. Since the compression process is isentropic, the entropy at the exit to the compressor is same as the entropy at the inlet, s_1 which is the saturated vapour entropy at evaporator pressure (known). Thus from the known pressure and entropy the exit state of the compressor could be fixed.

The quality (dryness fraction) of refrigerant at the inlet to the evaporator (x_4) could be obtained from the known values of h_3 , $h_{f,e}$ and $h_{g,e}$.

Once all the state points are known, then from the required refrigeration capacity and various enthalpies one can obtain the required refrigerant mass flow rate, volumetric flow rate at compressor inlet, COP etc.

Unit 3 Questions

Q1: Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. reversible cycle **b**. evaporator **c**. refrigerant **d**. isentropic **e**. turbine

1. The working fluid in vapour compression refrigeration system called _____.
2. Carnot refrigeration cycle is a completely _____.
3. Carnot refrigeration system for pure vapour consists of four components: compressor, condenser, _____ and evaporator.
4. Refrigeration effect, equal to the heat transferred at the _____ per kilogram of Refrigerant.
5. In standard vapour compression refrigeration system, the compression process is _____.

Q2: Which system component contains the described refrigerant conditions?

1. Low temperature, low pressure, saturated.
2. High temperature, high pressure, superheated.
3. High temperature, high pressure, saturated.

References:

1. Bill Whitman, Bill Johnson, John Tomczyk, Eugene Silberstein, Refrigeration and Air conditioning Technology, Sixth Edition, Delmar, Cengage Learning, 2009.

2. W. F. Stoecker, W.P. Jones, Refrigeration and air conditioning, Second Edition, McGraw-Hill.

Unit 4

Actual Vapour compression systems

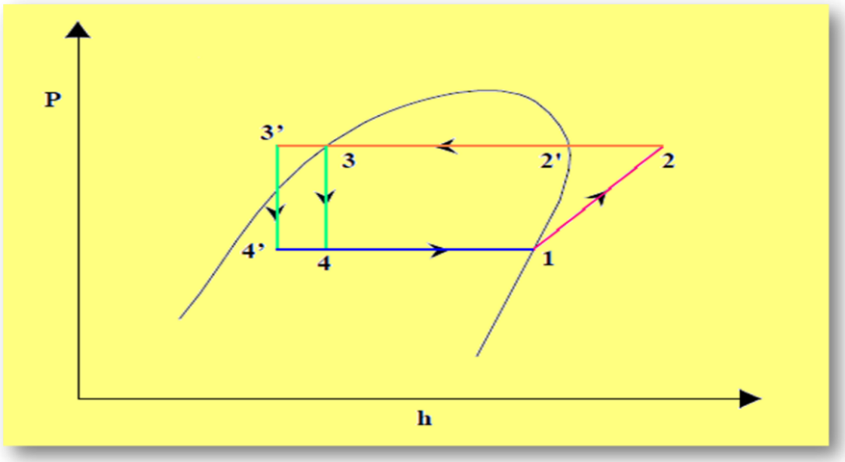
Subcooling and superheating:

In actual refrigeration cycles, the temperature of the heat sink will be several degrees lower than the condensing temperature to facilitate heat transfer. Hence it is possible to cool the refrigerant liquid in the condenser to a few degrees lower than the condensing temperature by adding extra area for heat transfer. In such a case, the exit condition of the condenser will be in the subcooled liquid region. Hence this process is known as **subcooling**.

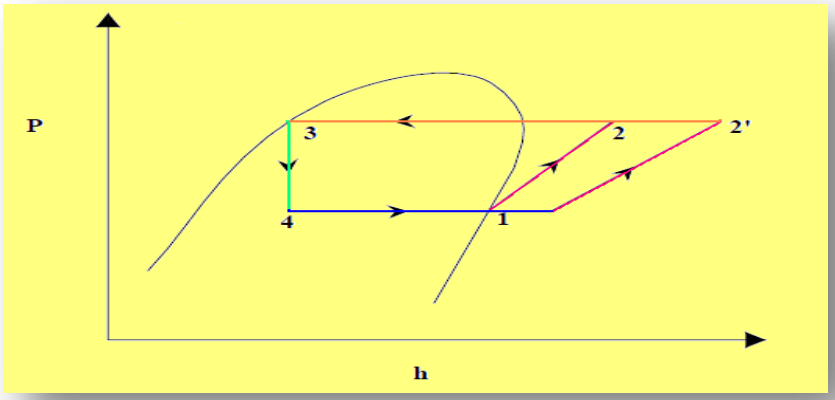
Similarly, the temperature of heat source will be a few degrees higher than the evaporator temperature, hence the vapour at the exit of the evaporator can be **superheated** by a few degrees. If the superheating of refrigerant takes place due to heat transfer with the refrigerated space (low temperature heat source) then it is called as useful superheating as it increases the refrigeration effect. On the other hand, it is possible for the refrigerant vapour to become superheated by exchanging heat with the surroundings as it flows through the connecting pipelines. Such a superheating is called as useless superheating as it does not increase refrigeration effect.

Subcooling is beneficial as it increases the refrigeration effect by reducing the throttling loss at no additional specific work input. Also subcooling ensures that only liquid enters into the throttling device leading to its efficient operation.

Figure below shows the cycle without and with subcooling on P-h diagram . The refrigeration effect increases by an amount equal to (h4-h4′) = (h3-h3′). Another practical advantage of subcooling is that there is less vapour at the inlet to the evaporator which leads to lower pressure drop in the evaporator.



Useful superheating increases both the refrigeration effect as well as the work of compression. Hence the COP (ratio of refrigeration effect and work of compression) may or may not increase with superheat, depending mainly upon the nature of the working fluid. Even though useful superheating may or may not increase the COP of the system, a minimum amount of superheat is desirable as it prevents the entry of liquid droplets into the compressor. Figure below shows the cycle with superheating on P-h diagram.



As shown in the previous figure, with useful superheating, the refrigeration effect, specific volume at the inlet to the compressor and work of compression increase. Whether the COP increase or not depends upon the relative increase in refrigeration effect and work of compression, which in turn depends upon the nature of the refrigerant used. The temperature of refrigerant at the exit of the compressor increases with superheat as the isentropes in the vapour region gradually diverge.

Liquid-Suction Heat Exchanger

Required degree of subcooling and superheating may not be possible, if one were to rely only on heat transfer between the refrigerant and external heat source and sink. Also, if the temperature of refrigerant at the exit of the evaporator is not sufficiently superheated, then it may get superheated by exchanging heat with the surroundings as it flows through the connecting pipelines (useless superheating), which is detrimental to system performance.

One way of achieving the required amount of subcooling and superheating is by the use of a liquid-suction heat exchanger (LSHX).

A LSHX is a counter flow heat exchanger in which the warm refrigerant liquid from the condenser exchanges heat with the cool refrigerant vapour from the evaporator.

Figure below shows the schematic of a single stage vapour compression refrigeration system with a liquid-suction heat exchanger.

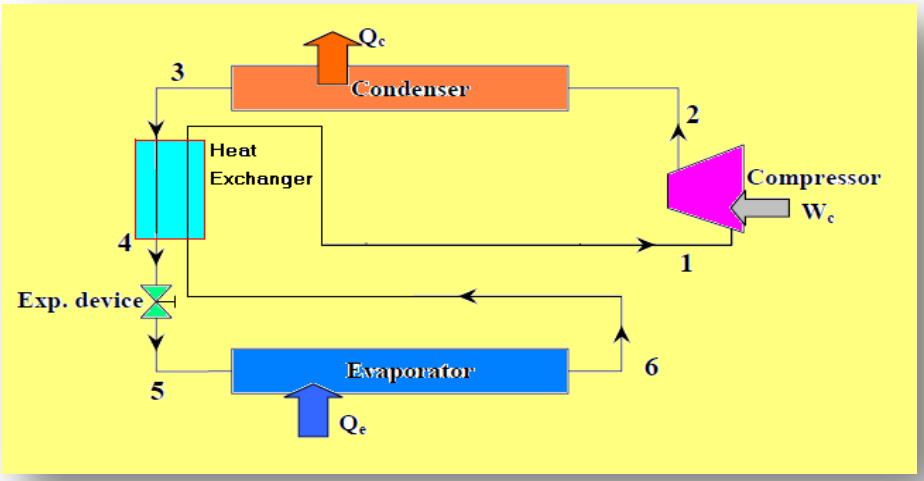
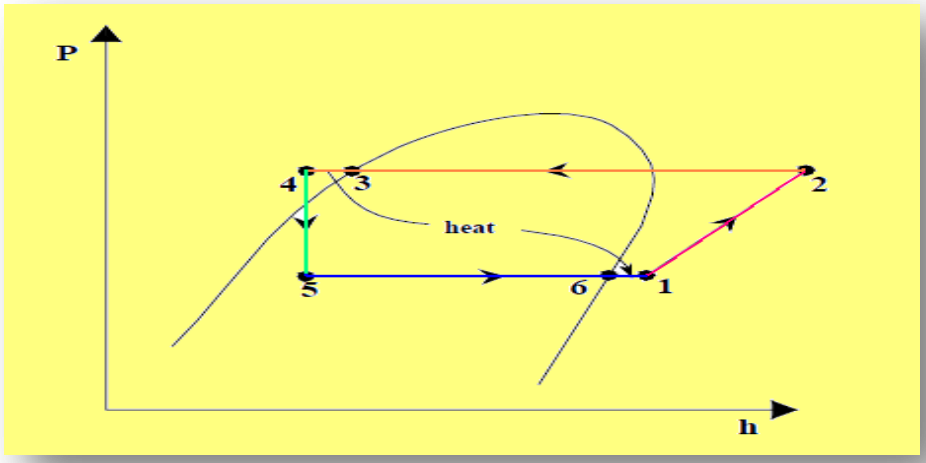


Figure shows the modified cycle on P-h diagram.

As shown in the diagram, since the temperature of the refrigerant liquid at the exit of condenser is considerably higher than the temperature of refrigerant vapour at the exit of the evaporator, it is possible to subcool the refrigerant liquid and superheat the refrigerant vapour by exchanging heat between them.



If we assume that there is no heat exchange between the surroundings and the LSHX and negligible kinetic and potential energy changes across the LSHX, then, the heat transferred between the refrigerant liquid and vapour in the LSHX, QLSHX is given by:

$$\dot{Q}_{LSHX} = \dot{m}_r (h_3 - h_4) = \dot{m}_r (h_1 - h_6)$$

$$\Rightarrow (h_3 - h_4) = (h_1 - h_6)$$

if we take average values of specific heats for the vapour and liquid, then we can write the above equation as;

$$c_{p,l}(T_3 - T_4) = c_{p,v}(T_1 - T_6)$$

since the specific heat of liquid (cp,L) is larger than that of vapour (cp,v), i.e., cp,L > cp,v, we can write:

$$(T_3 - T_4) < (T_1 - T_6)$$

This means that, the degree of subcooling (T3-T4) will always be less than the degree of superheating, (T1-T6). If we define the effectiveness of the LSHX, εLSHX as the ratio of actual heat transfer rate in the LSHX to maximum possible heat transfer rate, then:

$$\varepsilon_{LSHX} = \frac{Q_{act}}{Q_{max}} = \frac{\dot{m}_r\, c_{p,v}(T_1 - T_6)}{\dot{m}_r\, c_{p,v}(T_3 - T_6)} = \frac{(T_1 - T_6)}{(T_3 - T_6)}$$

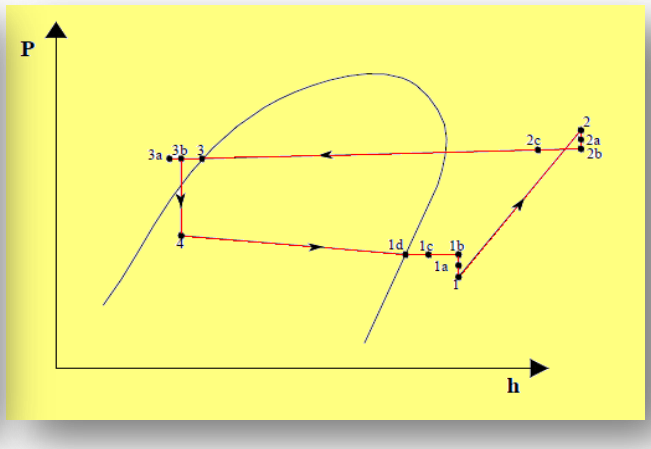
Actual Vapour Compression Refrigeration Systems:

The cycles considered so far are internally reversible and no change of refrigerant state takes place in the connecting pipelines. However, in actual vapour compression refrigeration system (VCRS) several irreversibilities exist.

These are due to:

1. Pressure drops in evaporator, condenser and LSHX.
2. Pressure drop across suction and discharge valves of the compressor.
3. Heat transfer in compressor.
4. Pressure drop and heat transfer in connecting pipe lines.

Process	State
Pressure drop in evaporator	4-1d
Superheat of vapour in evaporator	1d-1c
Useless superheat in suction line	1c-1b
Suction line pressure drop	1b-1a
Pressure drop across suction valve	1a-1
Non-isentropic compression	1-2
Pressure drop across discharge valve	2-2a
Pressure drop in the delivery line	2a-2b
Desuperheating of vapour in delivery pipe	2b-2c
Pressure drop in the condenser	2b-3
Subcooling of liquid refrigerant	3-3a
Heat gain in liquid line	3a-3b



Unit 4 Questions

Q1: Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

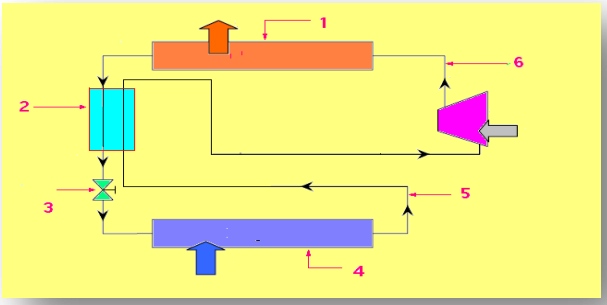
a. effectiveness **b**. volumetric efficiency **c**. liquid **d**. heat exchanger **e**. superheating

1. Useful _____ increases the refrigeration effect.
2. A minimum amount of superheat is desirable as it prevents the entry of _____ droplets into the compressor.
3. The _____ of the heat exchanger is the ratio of actual heat transfer rate in the heat exchanger to maximum possible heat transfer rate.
4. It is observed experimentally that some amount of superheat is good for the _____ of the compressor.
5. It is possible to subcool the refrigerant liquid and superheat the refrigerant vapour by using _____ .

Q2: Identify the points in the diagram shown below. Select your answers from the list, then print the letters in the appropriate blanks.

1. _____
2. _____
3. _____
4. _____
5. _____
6. _____

a. Evaporator
b. Suction line
c. Discharge line
d. Condenser
e. Heat exchanger
f. Expansion device



Q3: Select the correct answer(s) for the following questions.

1 :Subcooling is beneficial as it

a) Increases refrigeration effect

b) Decreases work of compression

c) Ensures liquid entry into expansion device

d) All of the above

2 :Superheating .

a) Always increases refrigeration effect

b) Always decreases specific work of compression

c) Always increases specific work of compression

d) Always increases compressor discharge temperature

3: Degree of superheating obtained using a LSHX is .

a) Always greater than the degree of subcooling

b) Always less than degree of subcooling

c) Always equal to degree of subcooling

d) Depends on the effectiveness of heat exchanger

4: In actual VCRS, the system performance is affected mainly by .

a) Pressure drop and heat transfer in suction line

b) Pressure drop and heat transfer in discharge line

c) Heat transfer in compressor

d) All of the above

5: Pressure drop and heat transfer in suction line .

a) Decrease compression ratio & discharge temperature

b) Increase compression ratio & discharge temperature

c) Decreases specific volume of refrigerant at suction

d) Increases specific volume of refrigerant at suction

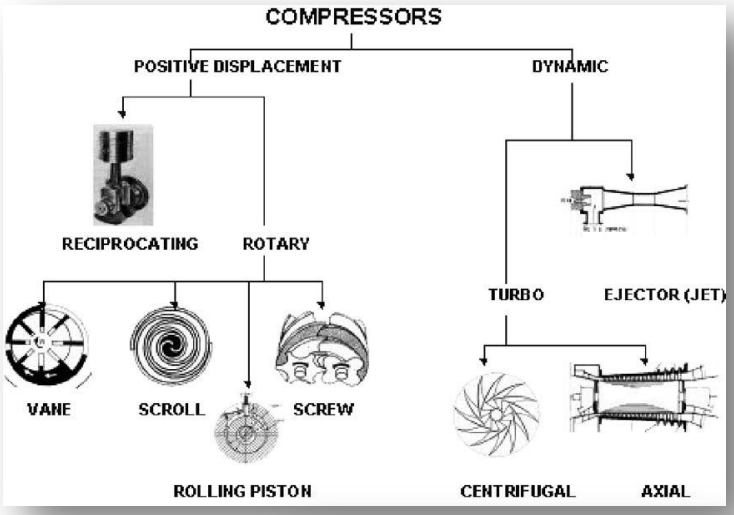
Unit 5

Compressors

A compressor is the most important and often the costliest component(typically 30 to 40 percent of total cost) of any vapour compression refrigeration system (VCRS). The function of a compressor in a VCRS is to continuously draw the refrigerant vapour from the evaporator, so that a low pressure and low temperature can be maintained in the evaporator at which the refrigerant can boil extracting heat from the refrigerated space. The compressor then has to raise the pressure of the refrigerant to a level at which it can condense by rejecting heat to the cooling medium in the condenser.

Classification of Compressors

Compressors used in refrigeration systems can be classified in several ways:

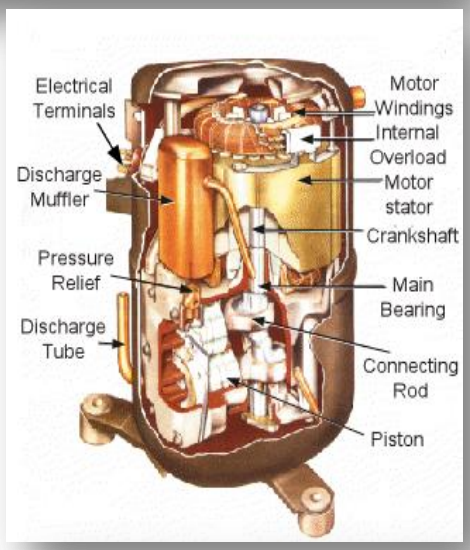


a) Based on arrangement of compressor motor or external drive:

1. Hermetic (or sealed) type
2. Semi-hermetic (or semi-sealed) type
3. Open type

b) Based on the working principle:

1. Positive displacement type
2. Roto-dynamic type

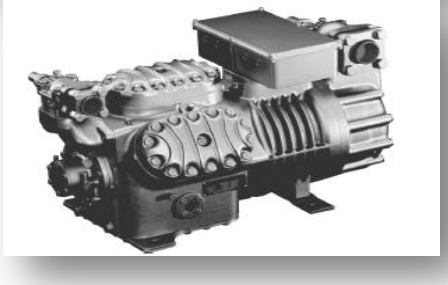


Hermetic Compressor

Hermetic means totally sealed. The hermetic compressor contains an electric motor that is connected directly to the compressor crankshaft. The entire assembly is enclosed within a welded steel housing. Welded hermetics dominate the residential and light commercial market because of their high reliability and quite operation

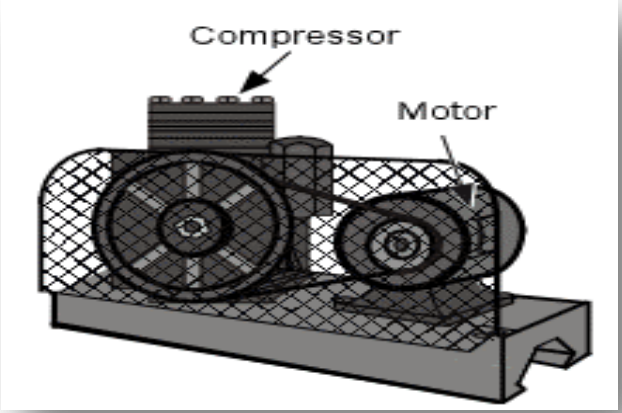
Semi-Hermetic Compressor

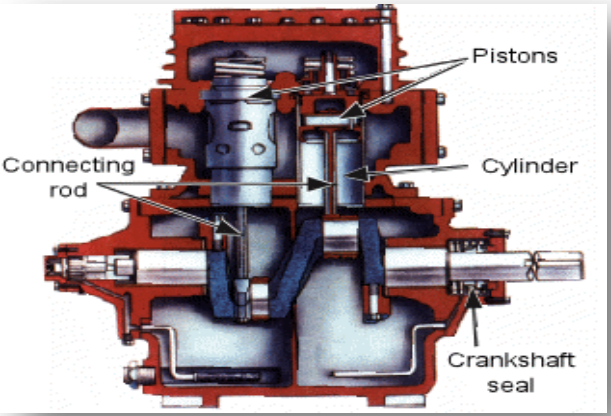
The semi-hermetic compressor is widely used for light, medium, and heavy duty commercial systems. The compressor is driven by an electric motor mounted directly on the crankshaft. The enclosure is bolted together, and gaskets are used to obtain leakproof seals between mating parts. Semi-hermetics can be totally disassembled in the field and fitted with new parts as needed.



Open Type Compressor

An open type compressor refers to a compressor that is driven by an external source of power, usually an electric motor. These compressors are bolted together with the crankshaft extending through the crankcase. A flywheel (pulley) is attached to the external crankshaft. An electric motor is connected to the crankshaft pulley by one or more V-belts.



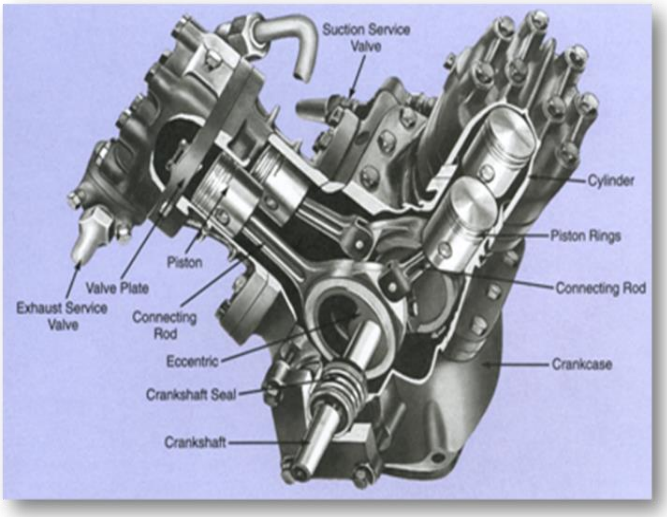


Positive Displacement Compressors

In positive displacement type compressors, compression is achieved by trapping a refrigerant vapour into an enclosed space and then reducing its volume. Since a fixed amount of refrigerant is trapped each time, its pressure rises as its volume is reduced.

Depending upon the construction, positive displacement type compressors used in refrigeration and air conditioning can be classified into:

1. Reciprocating type.
2. Rotary type (Stationary blade, Rotating blade).
3. Rotary scroll type.
4. Rotary screw type (single-screw or twin-screw).



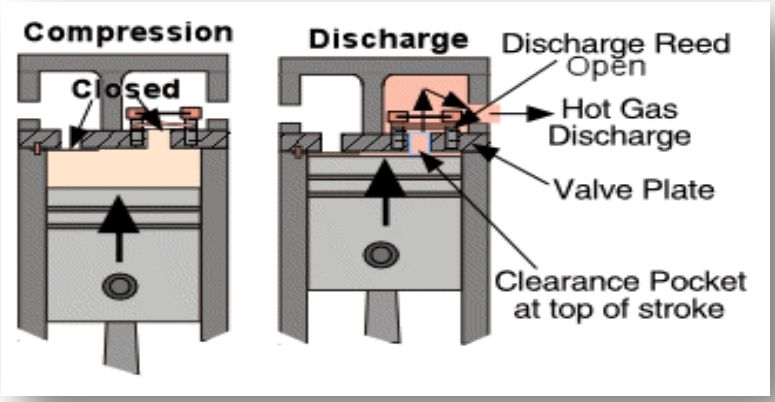
Reciprocating Compressors

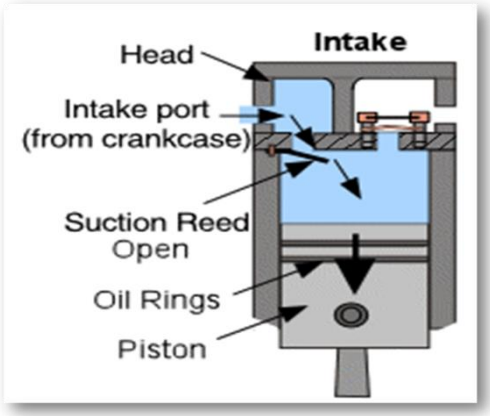
Reciprocating compressor is the workhorse of the refrigeration and air conditioning industry. It is the most widely used compressor with cooling capacities ranging from a few Watts to hundreds of kilowatts.

The Principle of Operation of Reciprocating Compressors

Basically, a reciprocating compressor is a cylinder and a piston, the piston has moved downward in the cylinder, it has moved refrigerant vapor from the suction line through the intake valve. From there the refrigerant vapor has moved into the cylinder space.

The piston has moved upward. It has compressed the vaporized refrigerant into a much smaller space (clearance space) The compressed vapor has been pushed through the exhaust valve into the condenser.

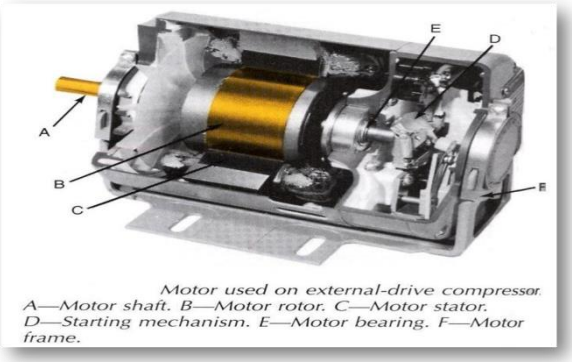




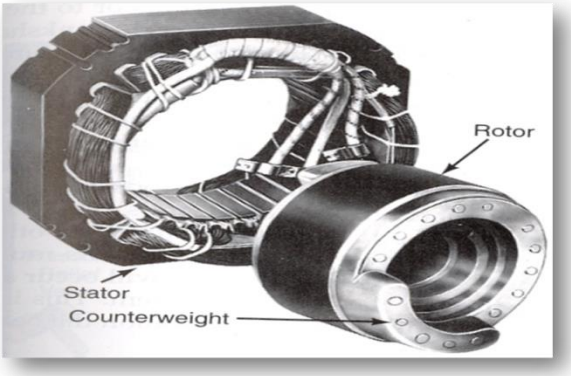
Compressors Motors

Two different types of motors are used for driving refrigeration compressors. External drive compressors use conventional motors. The compressor is driven with one or more V-belt or by direct drive .

In hermetic compressors, the motor is mounted under the same dome as the compressor. These motors are lubricated by the oil carried in the refrigerant. The compressor motor operating inside the refrigerant atmosphere must have special consideration. Motors for hermetic compressors differ from standard electric motors. The materials used in a hermetic motor are not the same materials that would be used in a fan or pump motor that would run in air. Hermetic motors must be manufactured of materials compatible with the system refrigerants.



Motor used on external-drive compressor. A—Motor shaft. B—Motor rotor. C—Motor stator. D—Starting mechanism. E—Motor bearing. F—Motor frame.



Rotary Compressors

Rotary compressors are also positive displacement machines but because of the rotary motion of their compressing mechanism, they operate smoother than reciprocating compressors.

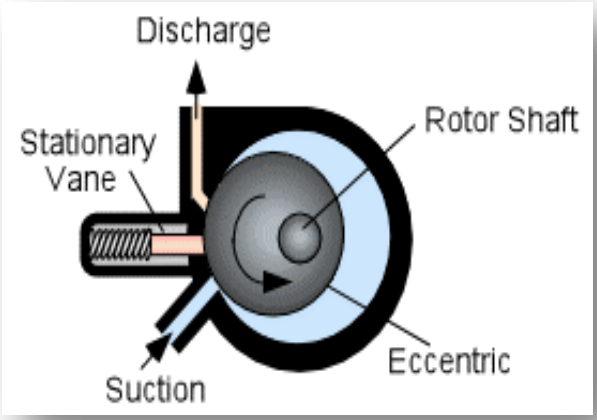
Rotary compressors are commonly used to power small refrigerated appliances such as window air conditioners, packaged terminal air conditioner, and heat pumps up to five tons. Rotary compressors are mostly used in low temperature industrial systems because they are more efficient than reciprocating compressors.

There are two basic types of rotary compressors :

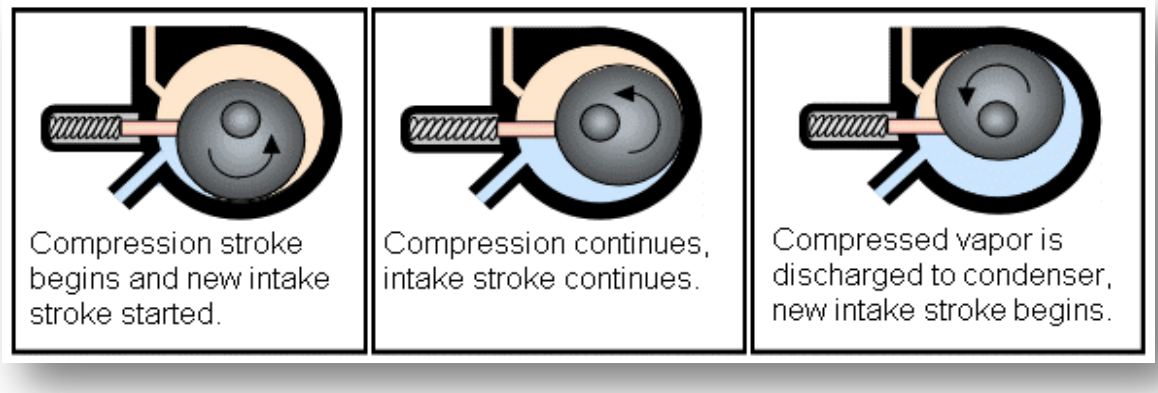
Stationary blade (vane) and Rotating blade .

Stationary Blade Compressor

The blade (vane) remains stationary and is part of the housing assembly. A cylindrical steel roller or piston rolls around the cylinder wall in the direction of crankshaft rotation. Refrigerant vapor is drawn into a space between the roller and the cylinder through a suction port from the evaporator suction line. As the roller continues to roll around the cylinder, the space ahead of the roller gets smaller. The vapour trapped ahead of the roller is compressed and forced out the discharge line. The roller continues on and a new space is made for the next cycle of refrigerant.

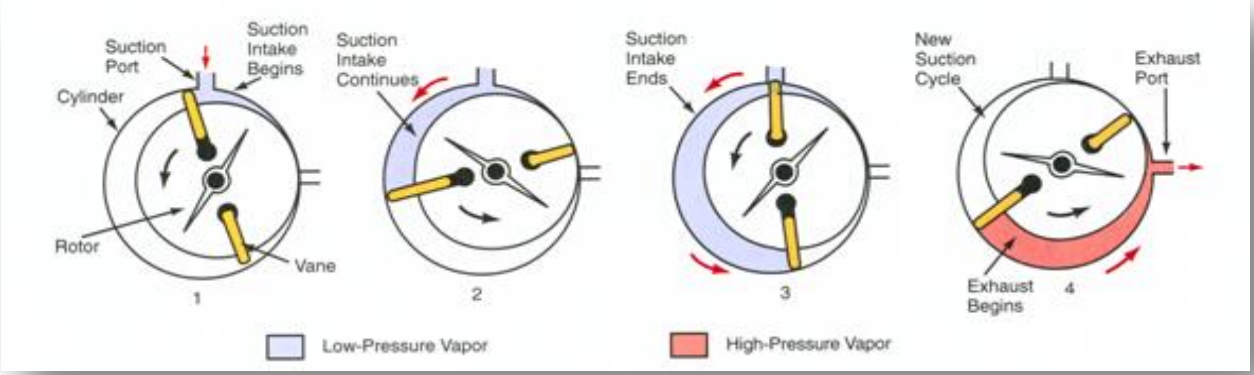


Operation of Stationary Blade Compressor



Rotating Blade Compressor

The rotating blade operates in a similar manner to the rolling piston. Blades are attached to a rotor and move back and forth in slots in the rotor as the rotor turns inside the cylinder wall. This maintains a positive seal against the walls. As the rotor turns, the space in the cylinder is reduced and the vapor is compressed. This compressor is frequently used as the "booster" compressor in cascade systems.



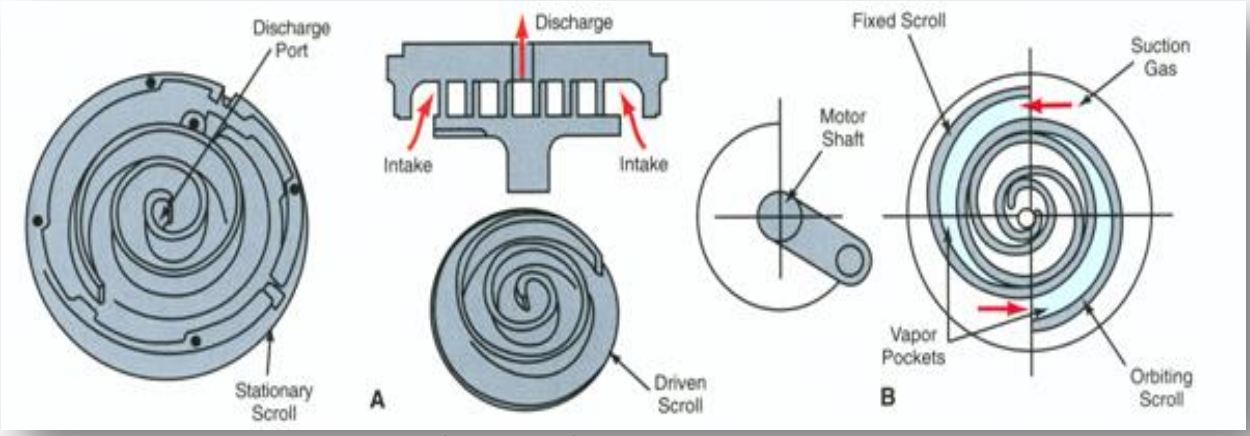
Scroll Compressors



The scroll compressor is commonly used in residential air conditioning and heat pump applications. Benefits of the scroll include fewer moving parts, less internal friction, smooth compression cycle with low torque, low noise levels, and low vibration levels.

A scroll compressor generates a series of crescent-shape gas pockets between two scrolls.

One scroll (the fixed) remains stationary, the other scroll (the orbiting) rotates through the use of the swing link. As the motion occurs, the pockets between the two forms are slowly pushed to the center of the two scrolls. This reduces the gas volume. When the pocket reaches the center of the scroll, the gas is at high pressure. It is discharged out of the center port.



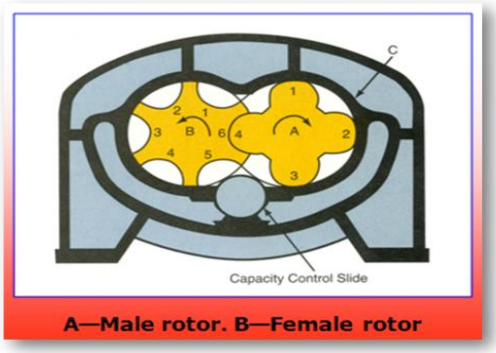
Screw Compressors

Screw compressors are often used in large-capacity systems ranging from 20 to 300 tons. They are offered as open, externally-drive compressors, or hermetic, internally-driven compressors.

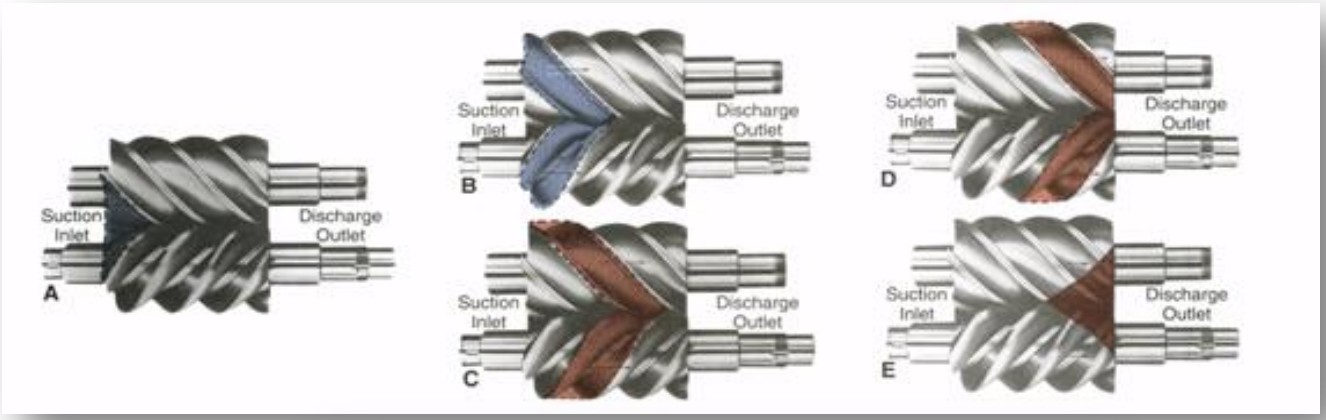
Open screw compressors are most often used with ammonia systems. Hermetic screw compressors are used with halocarbon refrigerants.

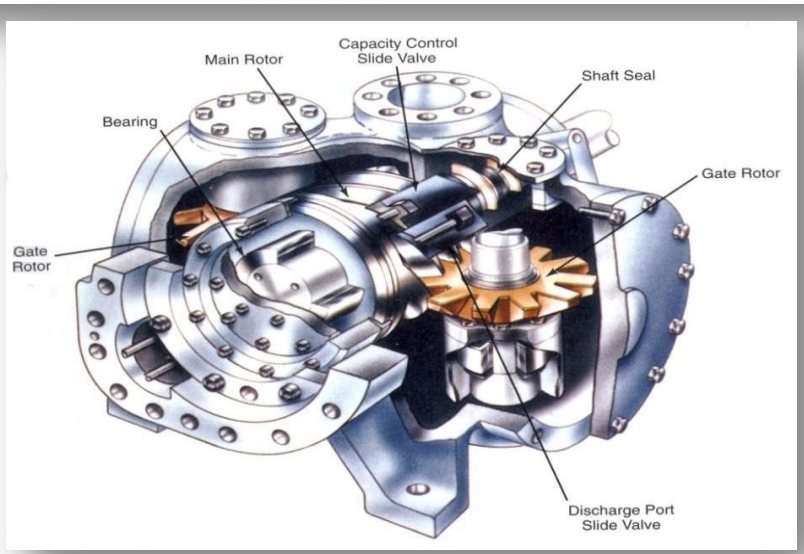
The screw compressor uses a pair of special helical rotors.

The two rotors are not the same shape. One is male, the other female. The male rotor, A , is driven by the motor. It has four lobes. The female rotor, B , meshes with and is driven by the male rotor. It has six interlobe spaces. The cylinder, C , encloses both rotors.



The intake (low-pressure vapour) enters at one end of the compressor and is discharged (compressed vapour) at the opposite end. The male rotor revolves more rapidly than the female rotor. The rotors are helixes. They provide a continuous pumping action rather than pulsating as with a reciprocating compressor. With this pumping action, there is very little vibration during operation.





Roto-Dynamic Compressors

the pressure rise of refrigerant is achieved by imparting kinetic energy to a steadily flowing stream of refrigerant by a rotating mechanical element and then converting into pressure as the refrigerant flows through a diverging passage. Unlike positive displacement type, the roto-dynamic type compressors are steady flow devices, hence are subjected to less wear and vibration. Depending upon the construction, roto-dynamic type compressors can be classified into:

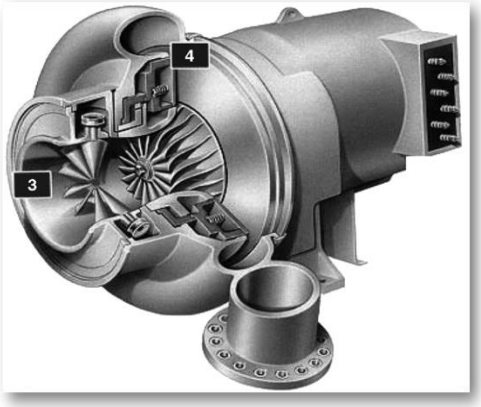
1. Radial flow type
2. Axial flow type

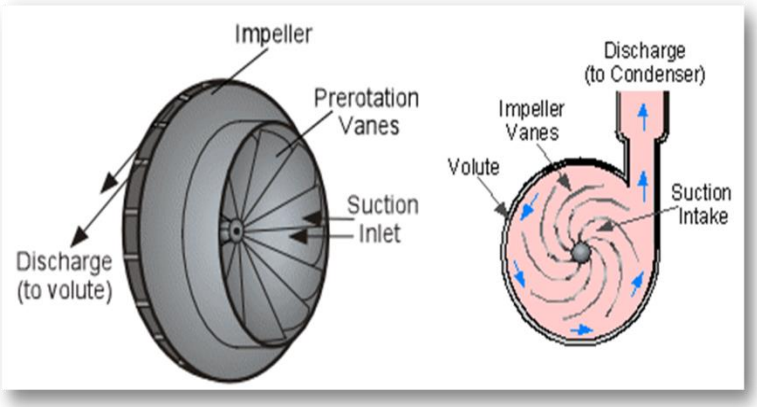
Centrifugal Compressors

Centrifugal compressors (also known as turbo-compressors) are radial flow type, roto-dynamic compressors. These compressors are widely used in large capacity refrigeration and air conditioning systems. Axial flow compressors are normally used in gas liquefaction applications.

Centrifugal compressors are designed for use with large capacity systems ranging in size from 50 to 5000 tons. In this type of compressor, vapour moves outward as it move rapidly in circular path. This action is called centrifugal force. The vapour is fed into a housing near the center of the compressor. A disk with radial blades (impellers) spins rapidly in the housing. This forces vapour against the outer diameter. Several impellers are put in series to multiply the pressure increase and further compress the vapour.

The centrifugal compressor has the advantages of simplicity. There are no valves or pistons and cylinders. The only wearing parts are the main bearings. Pumping efficiency increases with speed, so the compressors are designed to operate at high speeds.





Unit 5 Questions

Q1: Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. centrifugal **b**. rotary **c**. screw **d**. reciprocating **e.** roto-dynamic

1. _____ compressors consist of a piston moving back and forth in a cylinder.
2. There are two basic types of _____ compressors , stationary blade (vane) and rotating blade .
3. In _____compressor, the male rotor revolves more rapidly than the female rotor.
4. Unlike positive displacement type, the _____type compressors are steady flow devices.
5. _____compressors are designed for use with large capacity systems.

Q2: Answer the following questions.

1. Name two types of compressor drives.
2. Name five types of compressors.
3. On a reciprocating compressor, where are the discharge and suction valves located?
4. What type of compressor uses an impeller and volutes?
5. What terms describes the up and down action of pistons?

Q3: Select the correct answer(s) for the following questions.

1. Which of the following is not positive displacement type compressor?

a. Rotary vane compressor

b. Rotary screw type compressor

c. Centrifugal compressor

d. Acoustic compressor

2. Which compressor type uses pistons to compress the gas?

a. Scroll

b. Reciprocating

c. Rotary

d. Screw

3. Which style of compressor uses belts to turn the compressor?

a. Open drive

b. Closed drive

c. Chassis drive

d. Hermetic drive

4. A(n) _____ compressor does not use a crankshaft seal.

a. hermetic

b. open-type

c. semi-hermetic

d. None of the above

5. What type of compressor uses an impeller and volutes ?

a. Reciprocating

b. Rotary

c. Screw

d. Centrifugal

Unit 6

Condensers and Cooling Towers

Condensers are basically heat exchangers in which the refrigerant undergoes a phase change.

The purpose of the condenser in a vapour compression cycle is to accept the hot, high-pressure gas from the compressor and cool it to remove first the superheat and then the latent heat, so that the refrigerant will condense back to a liquid. In addition, the liquid is usually slightly subcooled. In nearly all cases, the cooling medium will be air or water.

Classification of Condensers:

Based on the external fluid, condensers can be classified as:

- Air cooled condensers
- Water cooled condensers
- Evaporative condensers

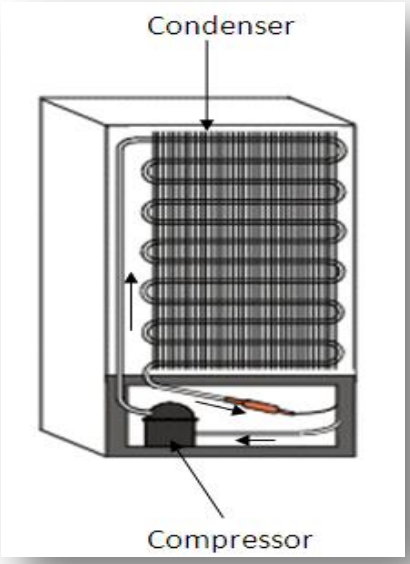
Air Cooled Condensers

In air-cooled condensers air is the external fluid (cooling medium), i.e., the refrigerant rejects heat to air flowing over the condenser. Air-cooled condensers can be further classified into natural convection type or forced convection type.

- **Natural convection condensers:**

In natural convection type, heat transfer from the condenser is by buoyancy induced natural convection and radiation. Since the flow rate of air is small and the radiation heat transfer is also not very high, the combined heat transfer coefficient in these condensers is small.

As a result a relatively large condensing surface is required to reject a given amount of heat. Hence these condensers are used for small capacity refrigeration systems like household refrigerators and freezers. The natural convection type condensers are either plate surface type or finned tube type.



The finned type condensers are mounted either below the refrigerator at an angle or on the backside of the refrigerator.

The fin spacing is kept large to minimize the effect of fouling by dust and to allow air to flow freely with little resistance.

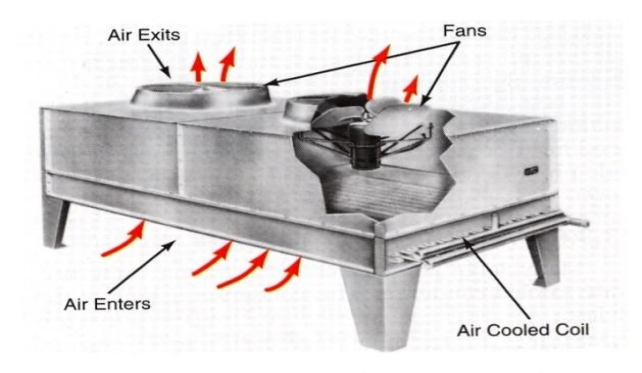
- **Forced convection condensers:**

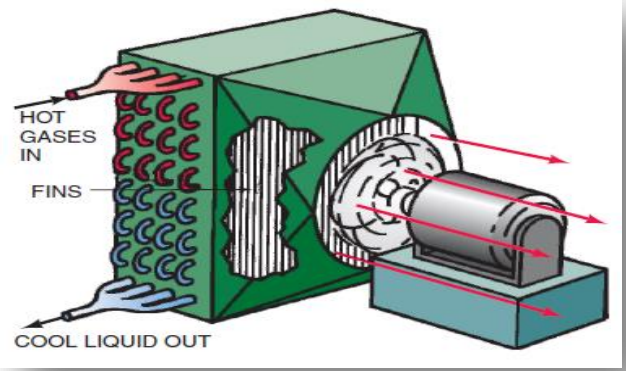
In forced convection type condensers, the circulation of air over the condenser surface is maintained by using a fan or a blower. These condensers normally use fins on air-side for good heat transfer. The fins can be either plate type or annular type.

The moist air flows over the fins while the refrigerant flows inside the tubes. The fins are usually of aluminum and tubes are made of copper.

Forced convection type condensers are commonly used in window and split air conditioners, water coolers and packaged air conditioning plants. These are either chassis mounted or remote mounted.

Air-cooled condensers are most often found on refrigeration and air conditioning systems, typically 200 tons or less. The reason for this is that large air-cooled condensers can take up considerable space and consume a good deal of electricity to operate the fans.





Water Cooled Condensers

In water cooled condensers water is the external fluid (cooling medium).

The higher heat capacity and density of water make it an ideal medium for condenser cooling.

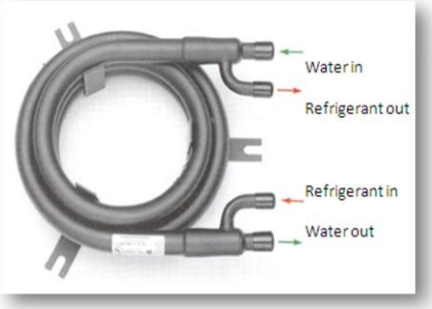
Depending upon the construction, water cooled condensers can be further classified into:

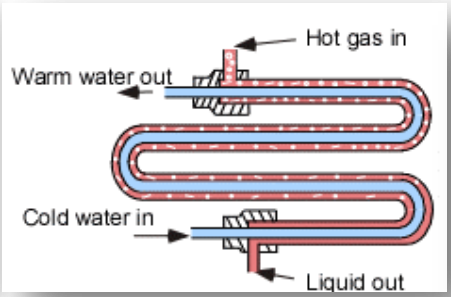
- Double pipe or tube in tube type
- Shell and coil type
- Shell and tube type

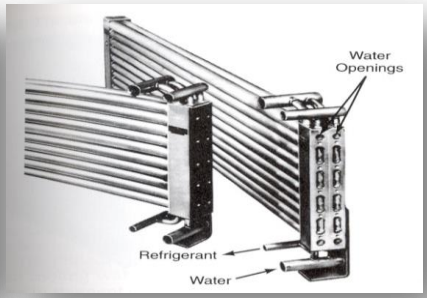
Double Pipe or Tube in Tube Condensers

Double pipe condensers are normally used up to 10 TR capacity. In these condensers the cold water flows through the inner tube, while the refrigerant flows through the annulus in counter flow. Headers are used at both the ends to make the length of the condenser small and reduce pressure drop.

The refrigerant in the annulus rejects a part of its heat to the surroundings by free convection and radiation. The heat transfer coefficient is usually low because of poor liquid refrigerant drainage if the tubes are long.

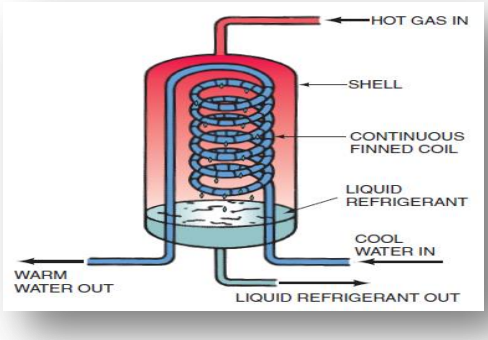






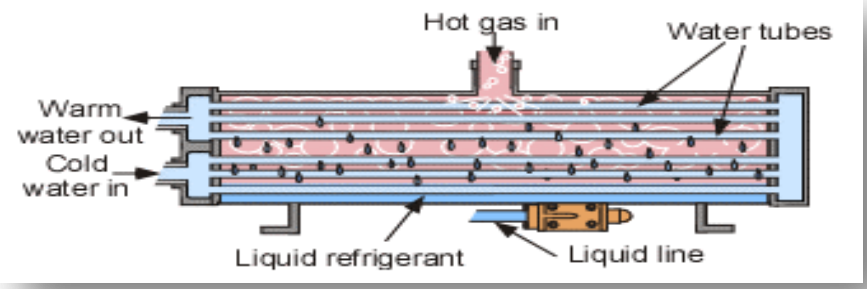
Shell and Coil Condensers

These condensers are used in systems up to 50 TR capacity. The water flows through multiple coils, which may have fins to increase the heat transfer coefficient. The refrigerant flows through the shell. In smaller capacity condensers, refrigerant flows through coils while water flows through the shell.



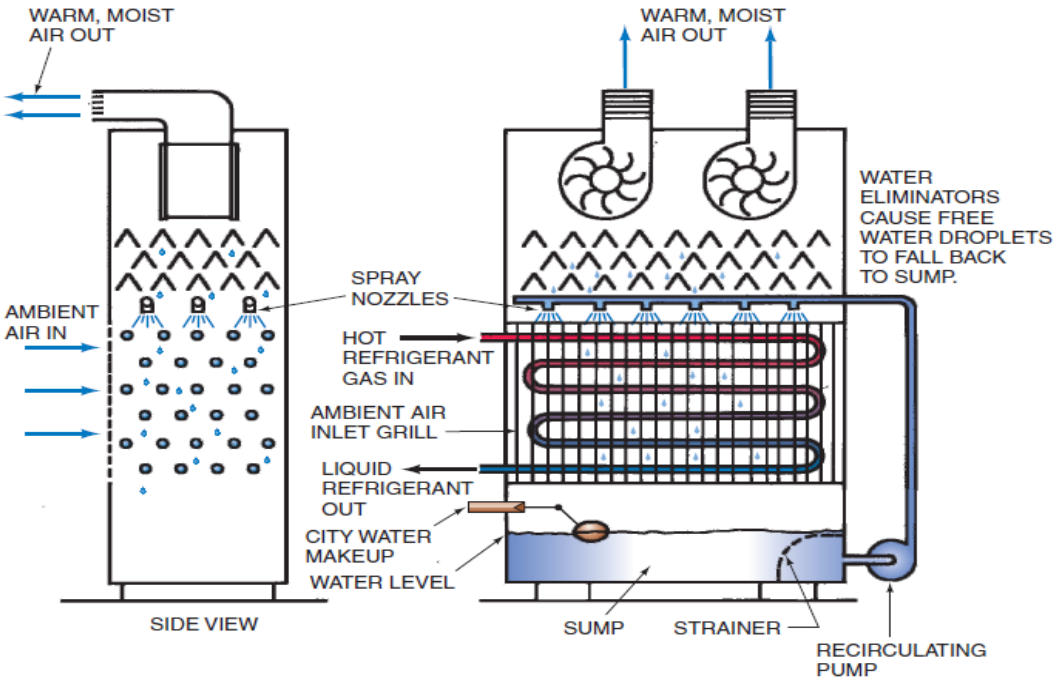
Shell and Tube Condensers

This is the most common type of condenser used in systems from 2 TR up to thousands of TR capacity. In these condensers the refrigerant flows through the shell while water flows through the tubes in single to four passes. The condensed refrigerant collects at the bottom of the shell. The coldest water contacts the liquid refrigerant so that some subcooling can also be obtained. The liquid refrigerant is drained from the bottom to the receiver.



Evaporative Condensers

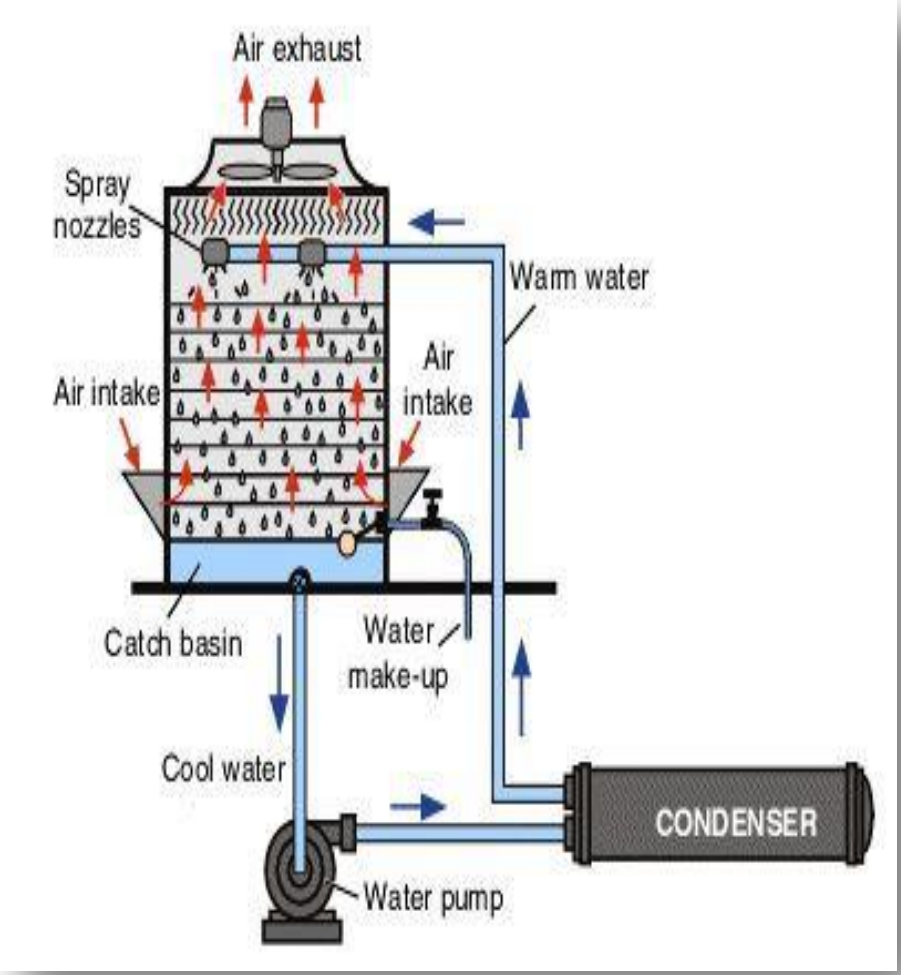
In evaporative condensers, both air and water are used to extract heat from the condensing refrigerant. Evaporative condensers combine the features of a cooling tower and water-cooled condenser in a single unit. In these condensers, the water is sprayed from top part on a bank of tubes carrying the refrigerant and air is induced upwards. There is a thin water film around the condenser tubes from which evaporative cooling takes place. The heat transfer coefficient for evaporative cooling is very large. Hence, the refrigeration system can be operated at low condensing temperatures . The water spray countercurrent to the airflow acts as cooling tower. The role of air is primarily to increase the rate of evaporation of water.



Evaporative condensers are used in medium to large capacity systems. These are normally cheaper compared to water cooled condensers, which require a separate cooling tower. Evaporative condensers are used in places where water is scarce. Since water is used in a closed loop, only a small part of the water evaporates. Make-up water is supplied to take care of the evaporative loss. The water consumption is typically very low, about 5 percent of an equivalent water cooled condenser with a cooling tower. However, since condenser has to be kept outside, this type of condenser requires a longer length of refrigerant tubing, which calls for larger refrigerant inventory and higher pressure drops.

Cooling Towers

The cooling tower is a device that passes outside air over the water to remove the system heat from the water. Any cooling tower is limited in capacity to the amount of evaporation that occurs. The evaporation rate is linked to the wet-bulb temperature of the outside air (humidity). A cooling tower cools water by a combination of heat and mass transfer. The water to be cooled is distributed in the tower by spray nozzles, splash bars, or film-type fill, which exposes a very large water surface area to atmospheric air.



Unit 6 Questions

Q1: Select the appropriate term from the list to complete the following statements, then print the letters in the proper blanks.

a. refrigerant **b**. forced convection **c**. cooling tower **d**. shell and tube **e.** natural convection **f**. evaporative condenser **g**. water

1. The _____ type condensers are either plate surface type or finned tube type.
2. _____ condenser is the most common type of water cooled condensers.
3. In evaporative condensers, both air and water are used to extract heat from the Condensing _____ .
4. The _____ is a device that passes outside air over the water to remove the system heat from the water
5. In _____ type condensers, the circulation of air over the condenser surface is maintained by using a fan or a blower .
6. _____ combine the features of a cooling tower and water-cooled condenser in a single unit.
7. In double pipe condensers the _____ flows throw the inner tube.

Ex-1 :

The condensing and evaporating temperatures in a simple refrigeration cycle working on (R-134 a) are (30 °C) and (- 30 °C) respectively. Find :

1. refrigeration effect (Q_e)
2. compressor work (W_C)
3. heat rejected from the condenser (Q_c)
4. coefficient of performance (COP)

HFC–134a Saturation Properties—Temperature Table

TEMP. °C	PRESSURE kPa (abs)	VOLUME m^3/kg LIQUID v_f	VOLUME m^3/kg VAPOR v_g	DENSITY kg/m^3 LIQUID $1/v_f$	DENSITY kg/m^3 VAPOR $1/v_g$	ENTHALPY kJ/kg LIQUID h_f	ENTHALPY kJ/kg LATENT h_{fg}	ENTHALPY kJ/kg VAPOR h_g	ENTROPY kJ/(kg)(K) LIQUID s_f	ENTROPY kJ/(kg)(K) VAPOR s_g	TEMP. °C
20	572.25	0.0008	0.0360	1224.4	27.791	227.5	182.5	410.0	1.0964	1.7189	20
21	590.16	0.0008	0.0349	1220.7	28.659	228.9	181.6	410.5	1.1012	1.7185	21
22	608.49	0.0008	0.0338	1217.0	29.549	230.4	180.7	411.0	1.1060	1.7182	22
23	627.25	0.0008	0.0328	1213.3	30.462	231.8	179.8	411.6	1.1107	1.7178	23
24	646.44	0.0008	0.0318	1209.6	31.399	233.2	178.9	412.1	1.1155	1.7175	24
25	666.06	0.0008	0.0309	1205.9	32.359	234.6	178.0	412.6	1.1202	1.7171	25
26	686.13	0.0008	0.0300	1202.1	33.344	236.1	177.0	413.1	1.1250	1.7168	26
27	706.66	0.0008	0.0291	1198.3	34.354	237.5	176.1	413.6	1.1297	1.7165	27
28	727.64	0.0008	0.0283	1194.4	35.389	238.9	175.2	414.1	1.1345	1.7161	28
29	749.04	0.0008	0.0274	1190.6	36.451	240.4	174.2	414.6	1.1392	1.7158	29
30	771.02	0.0008	0.0266	1186.7	37.540	241.8	173.3	415.1	1.1439	1.7155	30

HFC–134a Saturation Properties—Temperature Table

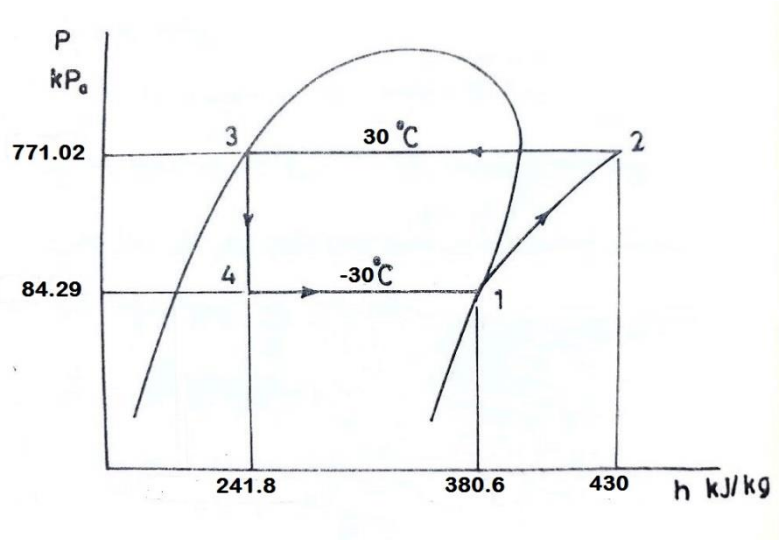
TEMP. °C	PRESSURE kPa (abs)	VOLUME m^3/kg LIQUID v_f	VOLUME m^3/kg VAPOR v_g	DENSITY kg/m^3 LIQUID $1/v_f$	DENSITY kg/m^3 VAPOR $1/v_g$	ENTHALPY kJ/kg LIQUID h_f	ENTHALPY kJ/kg LATENT h_{fg}	ENTHALPY kJ/kg VAPOR h_g	ENTROPY kJ/(kg)(K) LIQUID s_f	ENTROPY kJ/(kg)(K) VAPOR s_g	TEMP. °C
–40	51.14	0.0007	0.3614	1414.6	2.767	148.4	225.9	374.3	0.7967	1.7655	–40
–39	53.88	0.0007	0.3441	1411.8	2.906	149.6	225.3	374.9	0.8020	1.7641	–39
–38	56.74	0.0007	0.3279	1408.9	3.050	150.9	224.7	375.5	0.8073	1.7627	–38
–37	59.72	0.0007	0.3125	1406.0	3.200	152.1	224.0	376.2	0.8126	1.7613	–37
–36	62.83	0.0007	0.2980	1403.1	3.356	153.4	223.4	376.8	0.8178	1.7599	–36
–35	66.07	0.0007	0.2843	1400.2	3.518	154.6	222.8	377.4	0.8231	1.7586	–35
–34	69.43	0.0007	0.2713	1397.4	3.686	155.9	222.2	378.1	0.8283	1.7573	–34
–33	72.93	0.0007	0.2590	1394.5	3.861	157.1	221.5	378.7	0.8336	1.7561	–33
–32	76.58	0.0007	0.2474	1391.5	4.042	158.4	220.9	379.3	0.8388	1.7548	–32
–31	80.36	0.0007	0.2365	1388.6	4.229	159.7	220.3	379.9	0.8440	1.7536	–31
–30	84.29	0.0007	0.2260	1385.7	4.424	160.9	219.6	380.6	0.8492	1.7525	–30

1. $Q_e = h_1 - h_4$
$= 380.6 - 241.8$
$= 138.8$ kJ / kg

2. $W_C = h_2 - h_1$
$= 430 - 380.6$
$= 49.4$ kJ / kg

3. $Q_c = h_2 - h_3$
$= 430 - 241.8$
$= 188.2$ kJ / kg

4. $COP = Q_e / W_c$
$= 138.8 / 49.4$
$= 2.8$



Ex-2 :

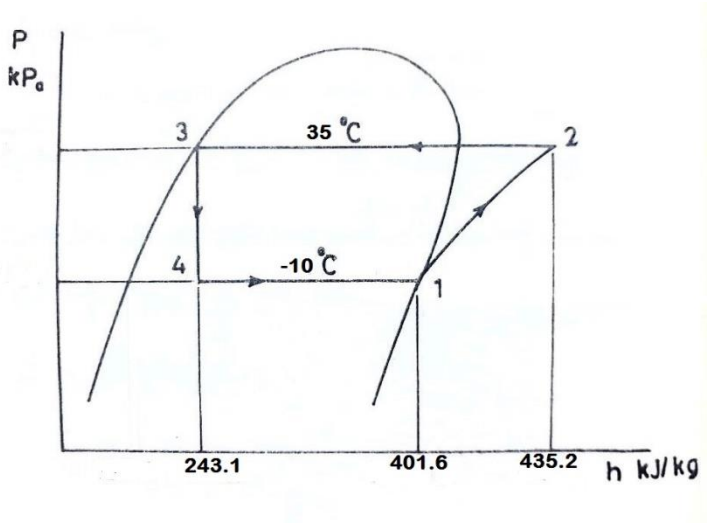
The condensing and evaporating temperatures in a simple air conditioning plant of **45 kW** capacity working on (R-22) are (35 °C) and (- 10 °C) respectively, Find :

1. refrigeration effect (Q_e)
2. mass flow rate of the refrigerant kg/s
3. compressor work (W_c)
4. coefficient of performance (COP)

1. $Q_e = h_1 - h_4$

$= 401.6 - 243.1$

$= 158.5$ kJ / kg



2. $Q = m_r (h_1 - h_4)$

$m_r = Q / h_1 - h_4$

$= 45 / 158.5$

$= 0.284$ kg / s

3. $W_c = h_2 - h_1$

$= 435.2 - 401.6$

$= 33.6$ kJ / kg

4. $COP = Q_e / W_c$

$= 158.5 / 33.6$

$= 4.717$

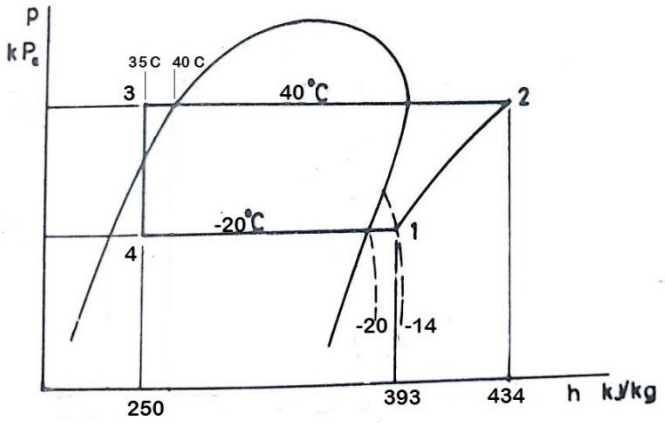
Ex : 3

Vapour compression system working on(**R134 a**) produce **30 kW** refrigeration capacity, the condensing and evaporating temperatures are (**40 °C**) and (**- 20 °C**) respectively. The refrigerant is subcooled by (**5 °C**) at the end of the condenser and superheated by (**6 °C**) before entering the compressor, calculate

a. the mass flow rate of the refrigerant

b. the heat rejected from the condenser in (kW)

c. the coefficient of performance (COP)



a. $Q_e = m_r (h_1 – h_4)$

$m_r = Q / (h_1 – h_4)$

$m_r = 30 / (393 – 250)$

$m_r = 0.209$ kg/s

b. $Q_c = m_r (h_2 – h_3)$

$Q_c = 0.209 (434 – 250)$

$Q_c = 38.45$ kW

c. $COP = Q_e / W_c$

$COP = (h_1 - h_4) / (h_2 - h_1)$

$COP = (393 – 250) / (434 – 393)$

$COP = 3.487$

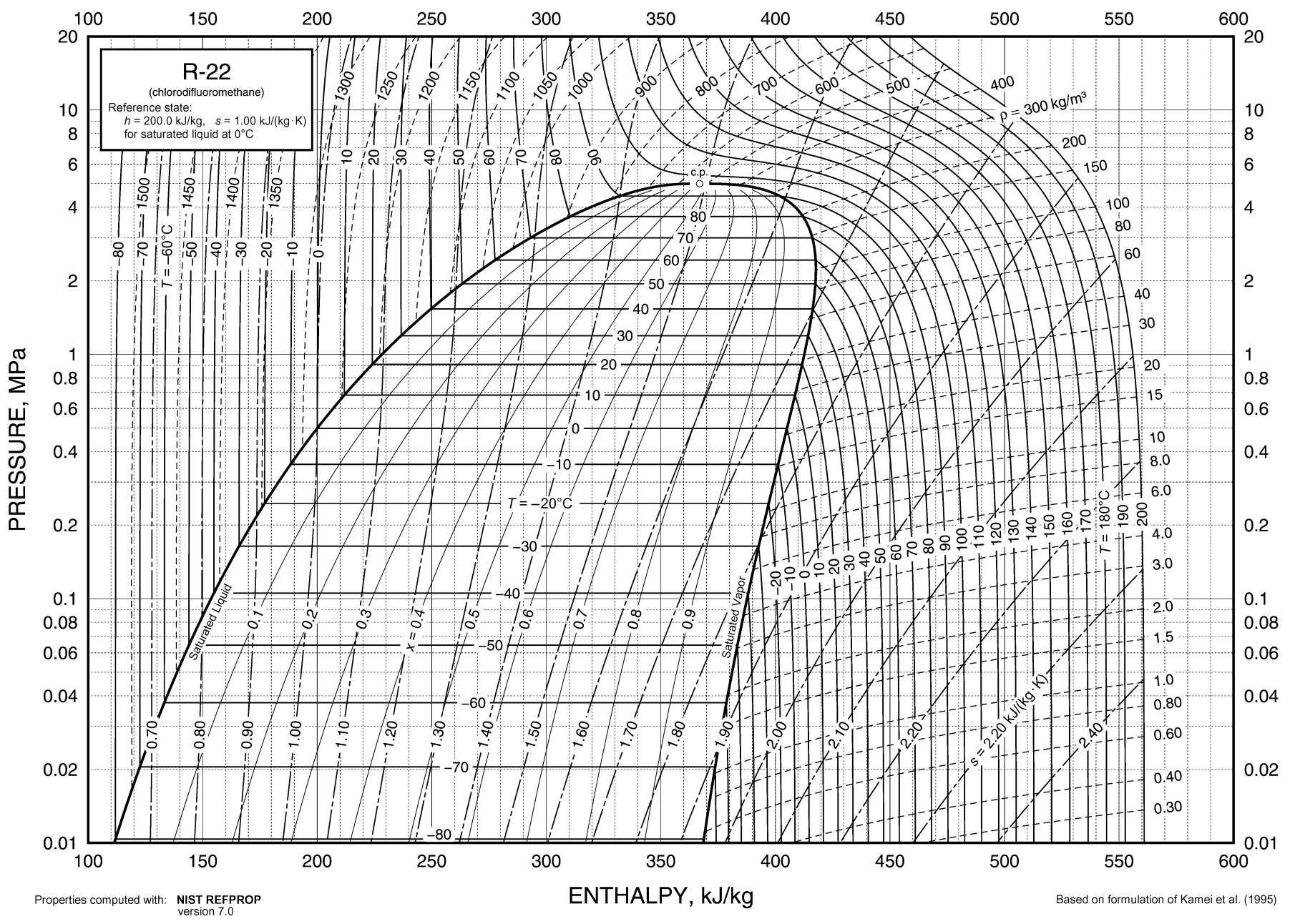


Fig. 2 Pressure-Enthalpy Diagram for Refrigerant 22

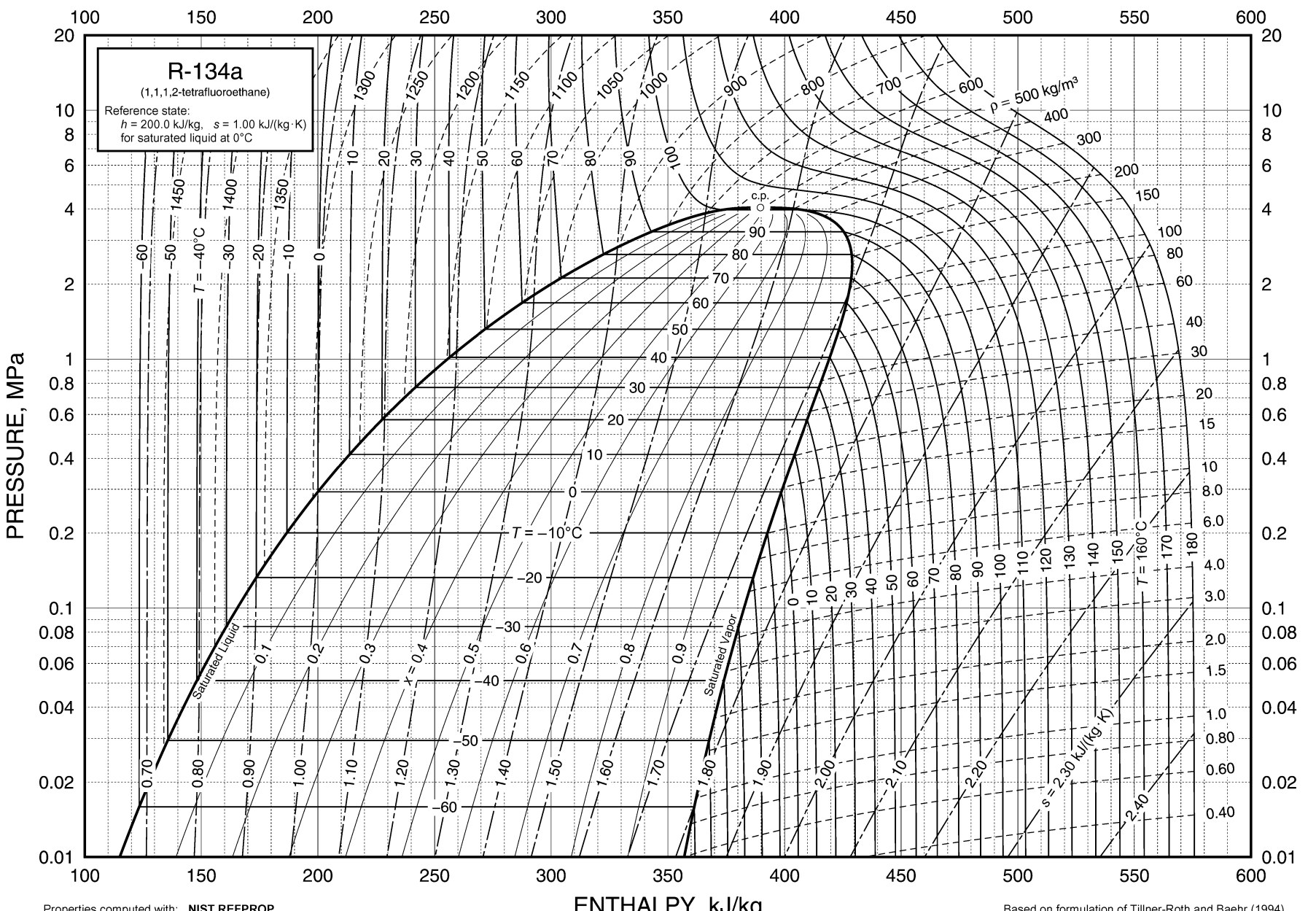


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a