Unit - V

Refrigeration & Air-Conditioning

Introduction

In heat engine, heat flow from hot body to cold body and produce useful work. If it operates in the reverse direction, it takes heat from a cold body and rejects it to a hot body by the external mechanical work known as reversed heat engine. This principle is used in heat pump and refrigerator.

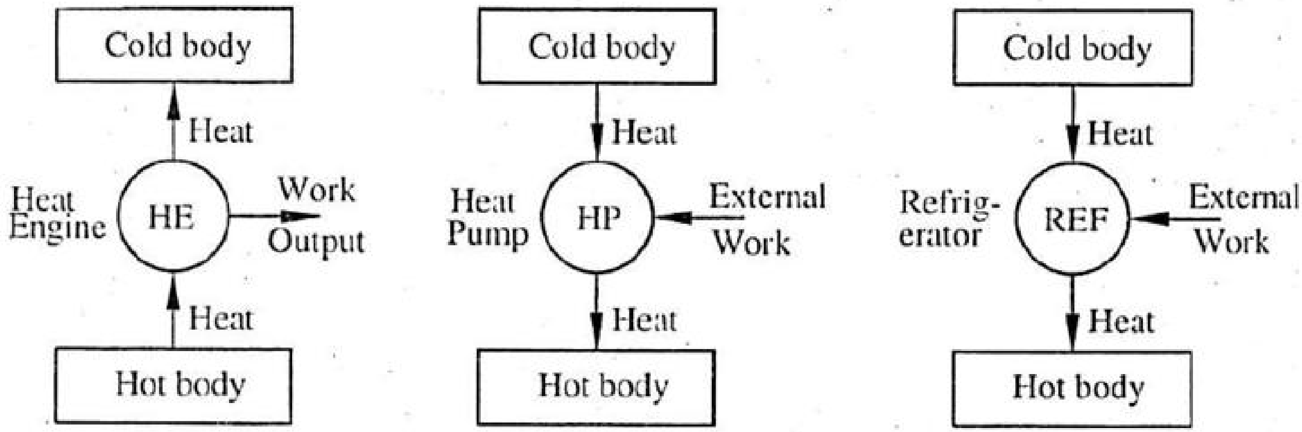

Figure 10.1 Heat Engine, Heat Pump and Refrigerator

Heat pump

It is device which absorbs the heat from cold body (surrounding) and deliver to hot body as shown in fig. 10.1 and maintain constant temperature of hot body for useful purpose. In this devise, external work required to convey heat from cold body to hot body.

Refrigerator

It is a device which removes heat from cold body and reject to hot body (surrounding) and maintains low temperature for useful purpose. In this device, external work is required to convey heat from cold body to hot body.

It is a device or system used to maintain the low temperature below the atmosphere temperature within required space.

Principle of refrigeration

In refrigeration, the heat is to be removed continuously from a system or space at a lower temperature and transfer to the surrounding at a higher temperature. In this process, according to second law of thermodynamics external work is required to convey heat from cold body to hot body. Therefore in refrigeration, power is required to cool the space below the atmospheric temperature.

Refrigeration is defined as the method of reducing the temperature of a system below surrounding temperature and maintains it at the lower temperature by continuously abstracting the heat from it. In simple, refrigeration means the cooling or removal of heat from a system.

Refrigerants

The refrigerant is a heat carrying medium which absorbs heat from space (desired to cool) and rejects heat to outside the refrigerator (in atmosphere). The refrigerant is working medium under goes various processes of refrigeration cycles which are used to produce refrigeration.

Properties of a good refrigerant

a) It should have high latent heat of evaporation and low specific volume.
b) It should have good thermal conductivity for rapid heat transfer.
c) It should be non-toxic, non-flammable and non-corrosive.
d) It should have low specific heat in liquid state and high specific heat in vapour state.
e) It should have high co-efficient of performance.
f) It should be economical in initial cost and maintenance cost.

Application of refrigeration

a) Storage and transportation of food stuffs as dairy products, fruits, vegetables, meat, fishes etc.
b) Preservation of medicines and syrups.
c) Manufacturing of ice, photographic films, rubber products.
d) Processing of petroleum and other chemical products.
e) Liquification of gases like N_2, O_2, H_2 etc.
f) Cooling water.
g) Comfort air conditioning of auditoriums, hospitals, residence, offices, factories, hotels, computer rooms etc.

Refrigerants commonly used in practice

1) NH_3 (Ammonia)

Properties

Highly toxic, flammable, good thermal properties, highest refrigerating effect per kg of refrigerant.

Uses

It is widely used in large industrial and commercial refrigeration system. It is mostly used with Vapour absorption refrigeration cycle like ice plants, cold storage, packing plants etc.

2) CO_2 (Carbon dioxide)

Properties

Colorless, non-toxic, non-flammable and non-corrosive gas. It gives low refrigeration effect.

Uses

It is used in marine refrigeration system.

3) Air

Properties

Easily available without cost, non-toxic, completely safe refrigerant, low COP.

Uses

It is used in aircraft air-conditioning system.

4) R-11 (Trichloro monofluoro methane) or Freon-11

Properties

Non-toxic, Non-flammable and Non-corrosive.

Uses

It is used in Small office buildings and factories for refrigeration.

5) R-12 (Dichlaro - difluro methane) or Freon -12

Properties

Non -toxic, Non-flammable, Non-explosive, high COP and most suitable refrigerant.

Uses

It is used in domestic vapour compression refrigeration.

6) R-22 (Monochloro - difluro methane) or Freon -22

Properties

Non-toxic, Non-flammable, Non-explosive Required less compressor displacement.

Uses

It is used in commercial and industrial low temperature applications (in air conditioning).

Refrigeration effect and unit of refrigeration

Refrigeration effect

It is define as the amount of heat absorbed by refrigerant from the space to be cooled.

The capacity of refrigeration system is expressed in tons of refrigeration which is unit of refrigeration.

1 ton of refrigeration

It is defined as refrigerating effect produced by melting of 1 ton of ice from and at 0°C in 24 hours.

OR

Amount of heat required to remove in order to form one ton of ice in 24 hours from water at temperature 0 °C.

The latent heat of ice is 335 kJ/kg, the refrigeration effect produced by 1 ton ice in 24 hours is,

$$= \frac{335 \times 1000}{24} KJ/hr = 14000\, KJ/hr = \frac{14000}{60} KJ/\min = 232.6\, KJ/\min = \frac{232.6}{60} KJ/s = 3.8888 KW$$

In actual practice, 1 ton = 900 kg considered for calculation of 1 ton of refrigeration,

$$\therefore 1 \text{ ton} = \frac{335 \times 900}{24} KJ/hr = 210\, KJ/\min = 3.5 KW$$

$$\therefore 1 \text{ ton of refrigeration} = 210\, KJ/\min = 3.5 KW$$

Bell-Coleman Cycle:

Working principle of the Bell Coleman air refrigeration system :

The *Bell Coleman air refrigeration system* is based on a reverse Joule cycle.

- The components of the Bell Coleman air refrigeration system are shown in figure (a). In this system, the air is taken into the compressor from the atmosphere and compressed.
- The hot compressed air is cooled in a heat exchanger up to the atmospheric temperature (in ideal conditions). The cooled air is then expanded in an expander.
- The temperature of the air coming out from the expander is below the atmospheric temperature due to isentropic expansion.
- The low-temperature air coming out from the expander enters into the evaporator and absorbs the heat. The cycle is repeated again.
- The working of the air refrigeration cycle is represented in figure (b).

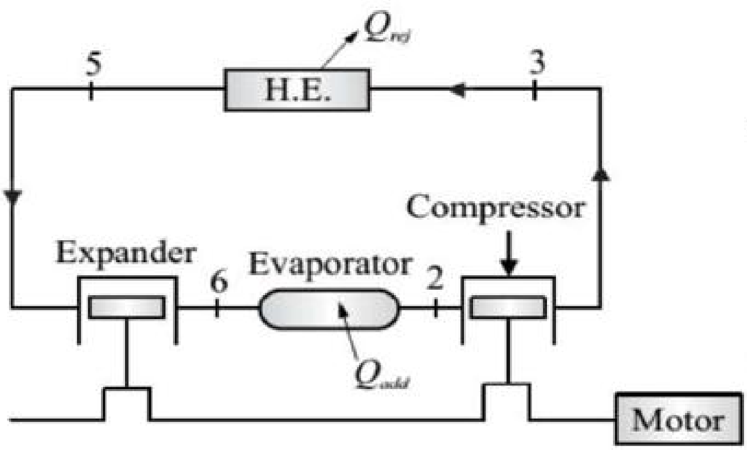

Fig. (a) : Air refrigeration cycle

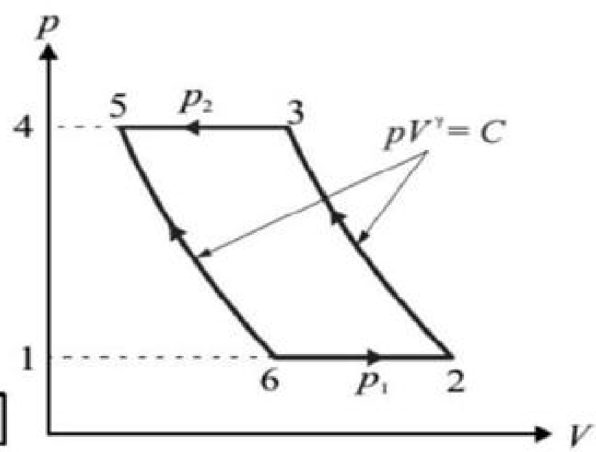

Fig. (b) : p-V diagram

Process (1-2): It represents the suction of air into the compressor.

Process (2-3): It represents the isentropic compression of air by the compressor.

Process (3-5): It represents the discharge of high-pressure air from the compressor into the heat exchanger. The reduction in the volume of air from V_3 to V_5 is due to the cooling of air in the heat exchanger.

Process (5-6): It represents the isentropic expansion of air in the expander.

Process (6-2): It represents the absorption of heat from the evaporator at constant pressure.

COP of Bell-coleman Cycle:

COP = Net refrigeration effect/ Net work supplied

Work done per kg of air for the isentropic compression process 2-3 is given by,

$W_c = C_p (T_3 - T_2)$

Work developed per kg of air for the isentropic expansion process 5-6 is given by,

$W_e = C_p (T_5 - T_6)$

Net work required :

$W_{net} = (W_c - W_e) = C_p (T_3 - T_2) - C_p (T_5 - T_6)$

The net refrigerating effect per kg of air is given by,

$Q_{addition} = C_p (T_2 - T_6)$

$$\text{COP} = \frac{Q_{add}}{W_{net}} = \frac{C_p(T_2 - T_6)}{C_p\{(T_3 - T_2) - (T_5 - T_6)\}}$$

For perfect inter-cooling, the required condition is $T_5 = T_2$

$$\text{COP} = \frac{(T_2 - T_6)}{(T_3 - T_2) - (T_2 - T_6)}$$

$$\text{COP} = \frac{1}{\frac{(T_3 - T_2)}{(T_2 - T_6)} - 1}$$

$$\text{COP} = \frac{1}{\frac{T_3\left(1 - \frac{T_2}{T_3}\right)}{T_2\left(1 - \frac{T_6}{T_2}\right)} - 1}$$

For isentropic compression process 2-3 and for expansion process 5-6,

$$\frac{T_3}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}}, \quad \frac{T_5}{T_6} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \quad \frac{T_3}{T_2} = \frac{T_5}{T_6}, \quad \frac{T_6}{T_5} = \frac{T_2}{T_3} \qquad [T_5 = T_2]$$

$$\text{COP} = \frac{T_2}{T_3 - T_2}$$

The advantages of the Bell coleman cycle are as follows:-

1. Simple in construction.
2. Air is used as refrigerant which is cheaply available and also non-toxic.
3. No harmful, if any leakage.
4. Low maintenance cost.

The disadvantages of the Bell coleman cycle are as follows:-

1. The system is bulkier hence weight per ton of refrigeration is higher.
2. High operation cost.
3. Less coefficient of performance (COP) as compared to other systems.

$$\text{COP} = \frac{Q_{add}}{W_{net}} = \frac{C_p(T_2 - T_6)}{C_p\{(T_3 - T_2) - (T_5 - T_6)\}}$$

For perfect inter-cooling, the required condition is $T_5 = T_2$

$$\text{COP} = \frac{(T_2 - T_6)}{(T_3 - T_2) - (T_2 - T_6)}$$

$$\text{COP} = \frac{1}{\frac{(T_3 - T_2)}{(T_2 - T_6)} - 1}$$

$$\text{COP} = \frac{1}{\frac{T_3\left(1 - \frac{T_2}{T_3}\right)}{T_2\left(1 - \frac{T_6}{T_2}\right)} - 1}$$

For isentropic compression process 2-3 and for expansion process 5-6,

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$$\text{COP} = \frac{T_2}{T_3 - T_2}$$

Desirable Properties of Refrigerants:

- An ideal refrigerant should have the following properties:
  1. Thermodynamic and thermo-physical properties
  2. Environmental and safety properties, and
  3. Economic Properties

1 Thermodynamic and thermo-physical properties

1.1 Suction Pressure

- At a given evaporator temperature, saturation pressure should be above atmospheric pressure for prevention of air into the system and ease of leak detection.
- Higher Suction pressure is better as the density is high & hence specific volume will be less & so the required size of the compressor will be smaller for a given mass flow rate.

1.2 Discharge Pressure

- At a given condenser temperature, the discharge pressure should be as small as possible to allow light weight construction of compressor, condenser, etc.

1.3 Pressure Ratio

- It should be as low as possible for high volumetric efficiency & low power consumption.

1.4 Latent Heat of Vaporization

- It should be as large as possible so that the required mass flow rate per unit cooling capacity will be small.

1.5 Liquid Specific Heat

- It should be small so that degree of sub-cooling will be large.

1.6 Vapour Specific Heat

- It should be large so that degree of superheating will be small.

1.7 Liquid and Vapour Thermal Conductivity

- It should high for better heat transfer.

1.8 Liquid and Vapour Viscosity

- It should be low for smaller frictional pressure drop.

1.9 Boiling & Freezing point

- At a given evaporator temperature, saturation pressure should be above atmospheric pressure for prevention of air into the system and ease of leak detectio
- Higher Suction pressure is better as the density is high & hence specific volume will be less & so the required size of the compressor will be smaller for a given mass flow rate.

2 Environmental & Safety Properties

2.1 Ozone Depletion Potential (ODP)

- It should be Zero i.e. no Chlorine or Bromine atoms.

2.2 Global Warming Potential (GWP)

- It should be Low.

2.3 Total Equivalent Warming Index (TEWI)

- It should be as small as possible. It will count direct & indirect contribution of refrigerant in Global Warming.

2.4 Toxicity

- It should be non-toxic.
- Refrigerants such as R-12 & R-22 are non-toxic in the presence of air. However in the presence of an open flame they decompose & release harmful gases.

2.5 Flammability

- It should be non-flammable & non-explosive.

2.6 Chemical Stability

- It should be chemically stabled & should not react within the system.

2.7 Compatibility with Common Materials

- It should not react with any material.

2.8 Dielectric Strength

- It should be high where refrigerant vapour comes into direct contact of electric motor windings e.g. hermetically sealed compressors

2.9 Ease of Leak Detection

- It should be easily detectable.

3 Economic Properties

3.1 Cost of Refrigerant

- It should be cheaper.

3.2 Availability

- It should be easily available

Common Refrigerants & its Properties

- The characteristics, properties and applications of some of the common refrigerants are discussed below:

Refrigerant	Properties	Applications
R-11 (CFC) $NBP = 23.7°C$ $h_{fg}\ at\ NBP = 182.5\frac{kJ}{kg}$ $T_{cr} = 197.98°C$ $ODP = 1$ $GWP = 3500$	▪ Non toxic ▪ Non flammable ▪ Non corrosive ▪ Low pressure refrigerant so specific volume is very high ▪ Need to use centrifugal compressor	▪ Large air conditioning systems ▪ Industrial heat pumps
R-12 (CFC) $NBP = -29.8°C$ $h_{fg}\ at\ NBP = 165.8\frac{kJ}{kg}$ $T_{cr} = 112.04°C$ $ODP = 1$ $GWP = 7300$	▪ Non toxic ▪ Non flammable ▪ Non corrosive ▪ Operating pressure is higher ▪ Most popular	▪ Domestic refrigerators ▪ Small air conditioners ▪ Small cold storages
R-22 (HCFC) $NBP = -40.8°C$ $h_{fg}\ at\ NBP = 233.2\frac{kJ}{kg}$	▪ Toxicity is similar to CO_2 ▪ Water is more soluble in R22 so driers & desiccants should be used	▪ Air conditioning systems ▪ Cold storages

$T_{cr} = 96.02°C$ $ODP = 0.05$ $GWP = 1500$	▪ Discharge temperature is high	
R-134a (HFC) $NBP = -26.15°C$ $h_{fg}\ at\ NBP = 222.5\frac{kJ}{kg}$ $T_{cr} = 101.06°C$ $ODP = 0$ $GWP = 1200$	▪ Non toxic ▪ Non flammable ▪ Immiscible in mineral oils so need to use synthetic lubricating oil ▪ Highly hygroscopic (tending to absorb moisture from air)	▪ Used as replacement of R12 in Domestic refrigerators ▪ Automobile A/Cs
R-717 (NH_3) $NBP = -33.35°C$ $h_{fg}\ at\ NBP = 1368.9\frac{kJ}{kg}$ $T_{cr} = 133°C$ $ODP = 0.$ $GWP = 0$	▪ Toxic & Flammable ▪ Incompatible with copper ▪ Highly efficient ▪ Inexpensive & easily available ▪ Discharge temperature is high so need to use water cooled compressors	▪ Cold storages ▪ Ice plants ▪ Food processing
R-744 (CO_2) $NBP = -78.4°C$ $h_{fg}\ at\ 40°C = 321.3\frac{kJ}{kg}$ $T_{cr} = 31.1°C$ $ODP = 0$ $GWP = 1$	▪ Non toxic ▪ Non flammable ▪ Critical temperature is very low so operate under very high pressure ▪ Inexpensive & easily available	▪ Earlier used in marine applications ▪ Cold storages

Co-efficient of performance

It is defined as the ratio of refrigerating effect to work required compressing the refrigerant in the compressor. It is the reciprocal of the efficiency of a heat engine. Thus the value of COP is greater than unity.

Mathematically, $COP = \dfrac{\text{Refrigerating effect}}{\text{Work of compressor}}$

Types of refrigerators

The refrigerator can be classified as follows.

1. Natural refrigerator

In natural refrigerator, the cooling effect produced by evaporation of liquid or sublimation of solids. When liquid evaporate, it absorbs heat from surrounding and produces cooling. Similarly, in sublimation (melting) of solid, it absorbs heat from surrounding and produces cooling effect.

2. Mechanical refrigerator

In mechanical refrigerator, refrigeration effect produced by, external source of mechanical energy or heat energy.

It is further classified as,

1. Vapour compression refrigerator
2. Vapour absorption refrigerator
3. Air refrigerator

Vapour Compression Refrigeration system (VCRS)

Construction

This system consist of (I) Evaporator (2) compressor (3) condenser and (4) expansion device. In vapour compression refrigerator, vapour used as the refrigerant. It is circulated in system in which it alternately evaporates (liquid to vapour) and condenses (vapour to liquid) thus it undergoes a change of phase. In the evaporation it absorbs the latent heat from the space to be cooled. In the condensing or cooling, it rejects heat to atmosphere.

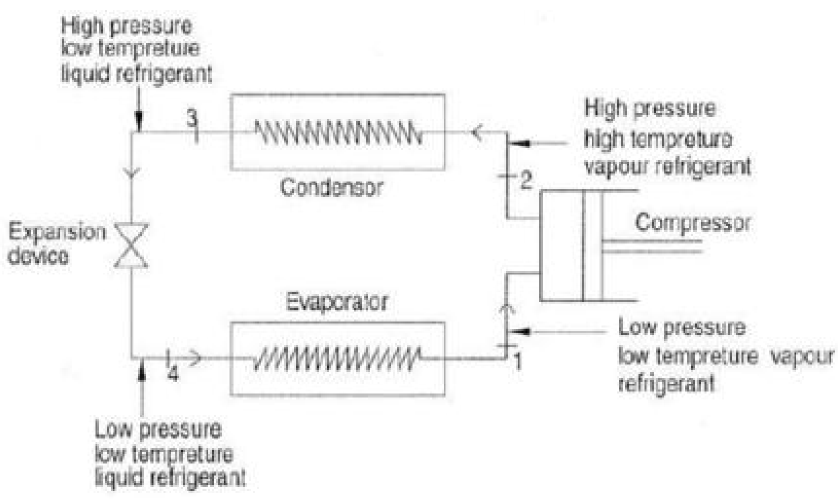


Fig. 10.2 Vapour compression refrigeration system

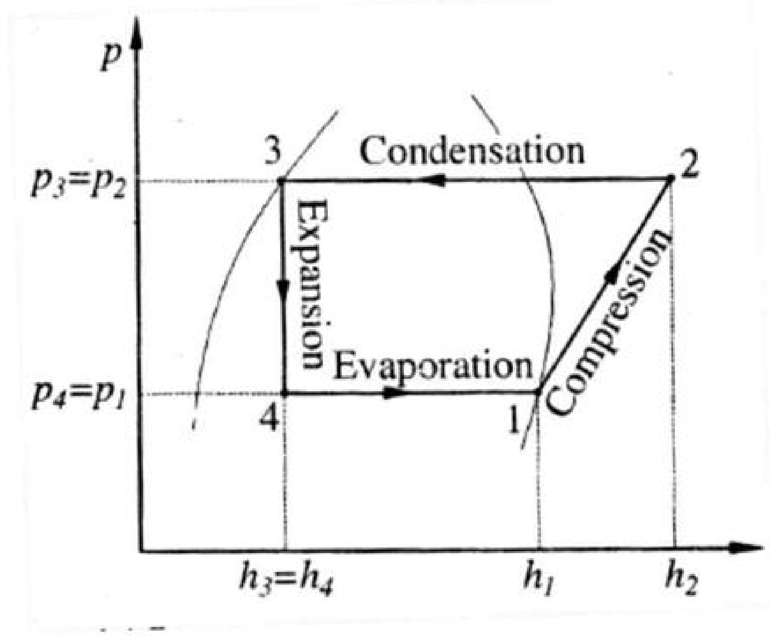


Fig. 10.3 P-h diagram

Functions of main parts of vapour compression system are,

Compressor

Function of compressor is to remove the vapour from the evaporator and increases its pressure and temperature up to it can be condensed in the condenser. Pressure of refrigerant coming from compressor should be such that the saturation temperature of vapour (corresponding to this pressure of vapour) is higher than the temperature of cooling medium in condenser. So that high pressure vapour can reject heat to cooling medium in the condenser.

Condenser

The function of condenser is to facilitate a heat transfer surface through which heat transfer takes place from the hot refrigerant vapour to the condensing medium. In domestic refrigerator condensing medium is atmospheric air.

Expansion valve or device

The function of expansion valve is to meter the proper amount of liquid refrigerant and reduces pressure of liquid refrigerant entering the evaporator. Hence liquid will vaporize in the evaporator at the desired low temperature and absorb heat from the space.

Evaporator

An evaporator provides a heat transfer surface through which low temperature liquid refrigerant can absorb heat from space and it vaporized.

Working

Process 1-2: Inlet of compressor (at point 1), low pressure and low temperature vapour enters the compressor. Compressor compresses the vapour at high temperature and pressure. The condition of refrigerant at exit to compressor (at point 2) is high pressure and high temperature vapour.

Process 2-3: High pressure, high temperature vapour coming from compressor condenses in the condenser by the rejecting heat to cooling medium. Cooling medium is usually air or water. The condition of refrigerant at exit to condenser (at point 3) is low temperature saturated liquid.

Process 3-4: The saturated liquid coming from condenser passes through expansion device (throttling valve) where pressure of saturated liquid decreases from condenser pressure to evaporator pressure. The condition of refrigerant after throttling is low temperature and low pressure liquid.

Process 4-1: Liquid refrigerant coming from expansion device enters into evaporator where it absorbs latent heat of evaporation from space to be cooled (refrigerator compartment). Due to absorption of heat liquid refrigerant converted into saturated vapor or superheated vapour at low pressure and low temperature. Again this vapour enters into compressor and the cycle is repeated.

Domestic vapour compression refrigerator

Construction

It consists of an evaporator installed in the freezing compartment of the refrigerator. One end of evaporator connected to the suction side of the compressor and other end connected to condenser through throttle valve. Normally condenser installed at the backside of refrigerator. The delivery side of compressor is connected to a condenser.

Examples available in capacities of 65 liters, 100 liters, 165 liters, 275litres,1000 liters.

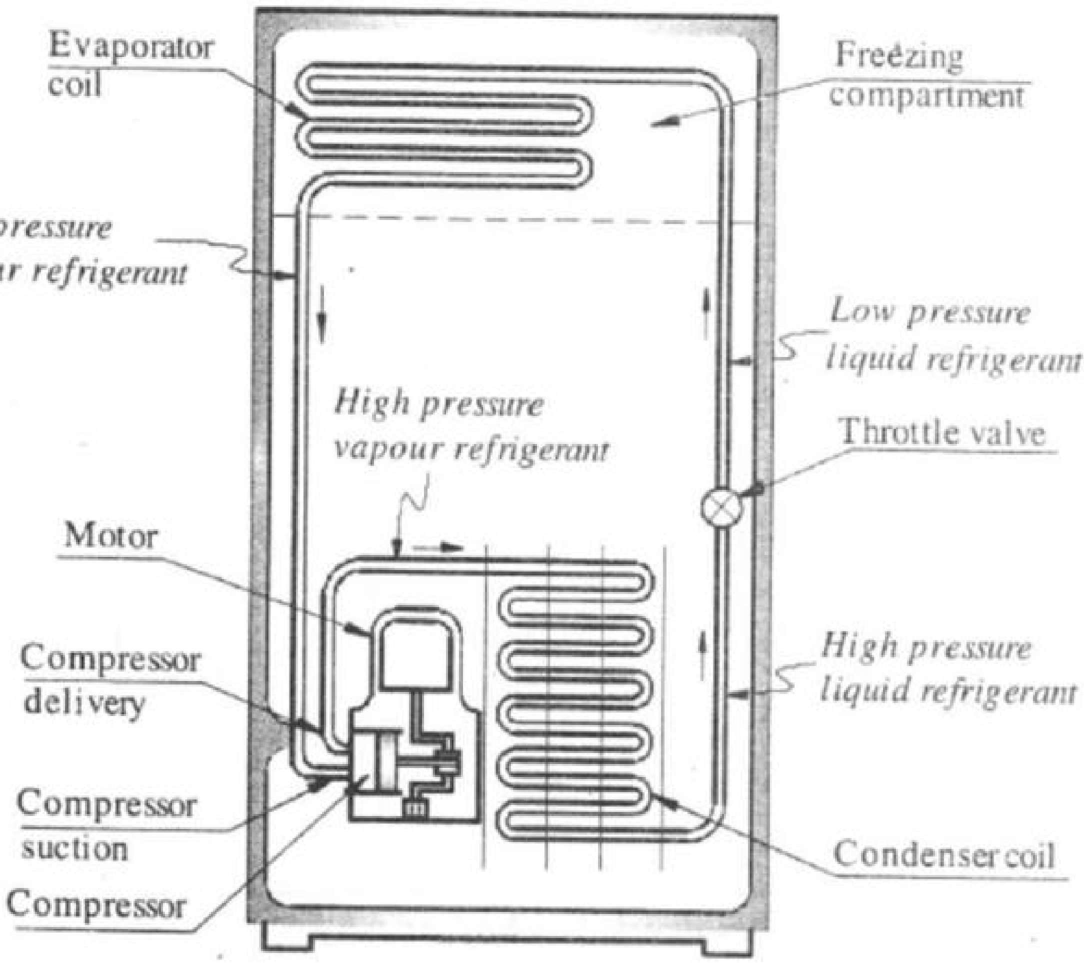


Fig. 10.4 Domestic vapour compression refrigerator

Vapour Absorption Refrigeration System (VARS)

Construction

This system is shown in figure consists of (i) evaporator, (ii) condenser, (iii) generator, (iv) absorber, (v) pump and (vi) expansion device. In this system the refrigerant coming from evaporator is absorbed by absorber. The absorbing medium may be solid or liquid. In VAR system, the compressor is replaced by an absorber and generator.

Ammonia is refrigerant has characteristic as it is easily absorbed by water at low pressure and temperature, but at high pressure and temperature, the solubility of ammonia in water is reduced. Therefore when mixture of water and ammonia is heated by generator, the ammonia vapour is separated from water.

This principle is used in the vapour absorption refrigeration system. Here the ammonia is refrigerant and water is absorbent.

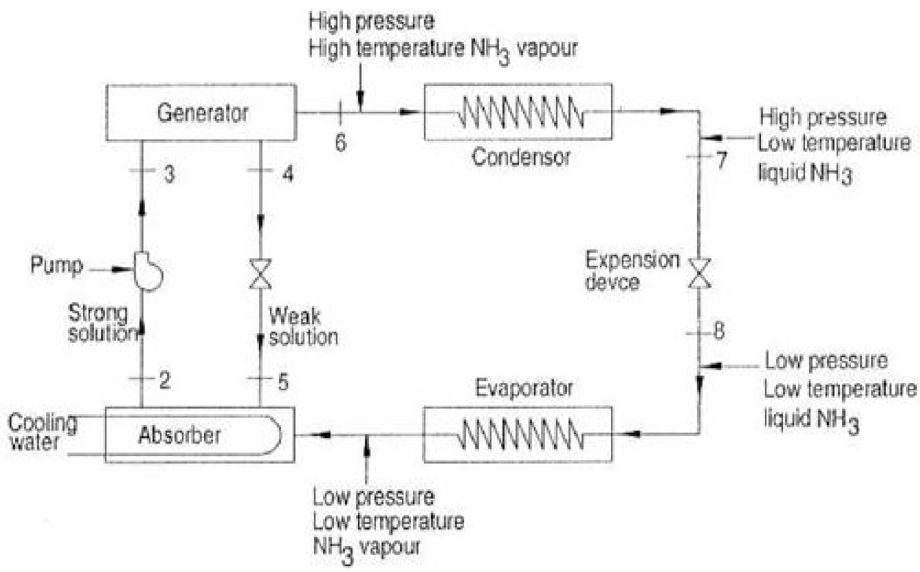


Fig. 10.5 vapour absorption refrigeration system

Working

Low pressure and low temperature vapour ammonia coming from evaporator enters in the absorber where ammonia is absorbed by weak solution coming from generator through throttle valve at point 5. Due to absorption of NH_3 in water, solution becomes strong. [In the mixture of NH_3 and water, if amount of NH_3 is less than water is called weak solution and if amount of NH_3 is more than the water is called strong solution.] During absorption process heat is released and rejected to cooling water.

The strong solution from absorber is pumped into generator, where it is heated and NH_3 vapour separated from solution. In generator is supplied from external source. The weak solution at point 4 is flowing back to absorber through throttle valve. Again weak solution in absorber absorbs NH_3 vapour coming from evaporator.

NH_3 vapour coming from generator (at point 6) passes through condenser and condensed in condenser and reject heat to cooling medium. Then liquid NH_3 (at point 7) throttled through expansion device and it enters into evaporator (point 8). In the evaporator NH_3 evaporates by absorbing latent heat of evaporation produce refrigerating effect. Thus the cycle is completed.

Comparison between vapour compression and vapour absorption systems

Table 10.1 Comparison between VCR and VAR

Sr. No	Particulars	Vapour compression system (VCR)	Vapour Absorption system (VAR)
1.	Working method	Refrigerant vapour is compressed	Refrigerant is absorbed and heated
2.	Type of the energy Supplied	Mechanical work supply to compressor	Heat energy supply to generator
3.	Input work required	More compression work is required	Less mechanical energy is required to run pump
4.	COP	High (Approx. 3)	Low (Approx. 0.6)
5.	Capacity	Limited up to 1000 tons for single compressor	It may be above 1000 tons
6.	Noise	More	Quiet operation
7.	Leakage	More leakage due to high pressure	Almost there is no Leakage
8.	Operating cost	High because of compressor consumes more work	Less because of less heat energy is required
9.	Suitable refrigerant	R-12	Ammonia

Superheating & Subcooling

- Saturated – condition of a liquid at its boiling temperature, and of a vapor at its condensing temperature:
- Superheated – vapor at a temperature above its saturation temperature
- Subcooled – liquid at a temperature below its saturation temperature
- Pressure and Saturation Relationship
    - As the pressure increases, saturation temperature will increase. As the pressure decreases, the saturation temperature decreases.

- **Superheat is defined as the amount of heat added to a vapor above its boiling point.**
- As the cold vapor flows though the evaporator, it continues to absorb heat, and becomes superheated. As the vapor becomes superheated, it absorbs sensible heat in the evaporator. Thus, the effect of refrigeration for every pound of refrigerant is enhanced.
- Refrigerant absorbs not only the heat required to vaporize it, but also an extra quantity of sensible heat, due to which it is superheated
- Effect of Superheating:

❑ Superheating is the sensible heating of refrigerant vapor at invariable pressure in the evaporator to a temperature more than the temperature of saturation corresponding to the evaporator pressure. Though the effect of refrigeration is increased by superheating, the density of vapor which quits the evaporator and enters the compressor is reduced

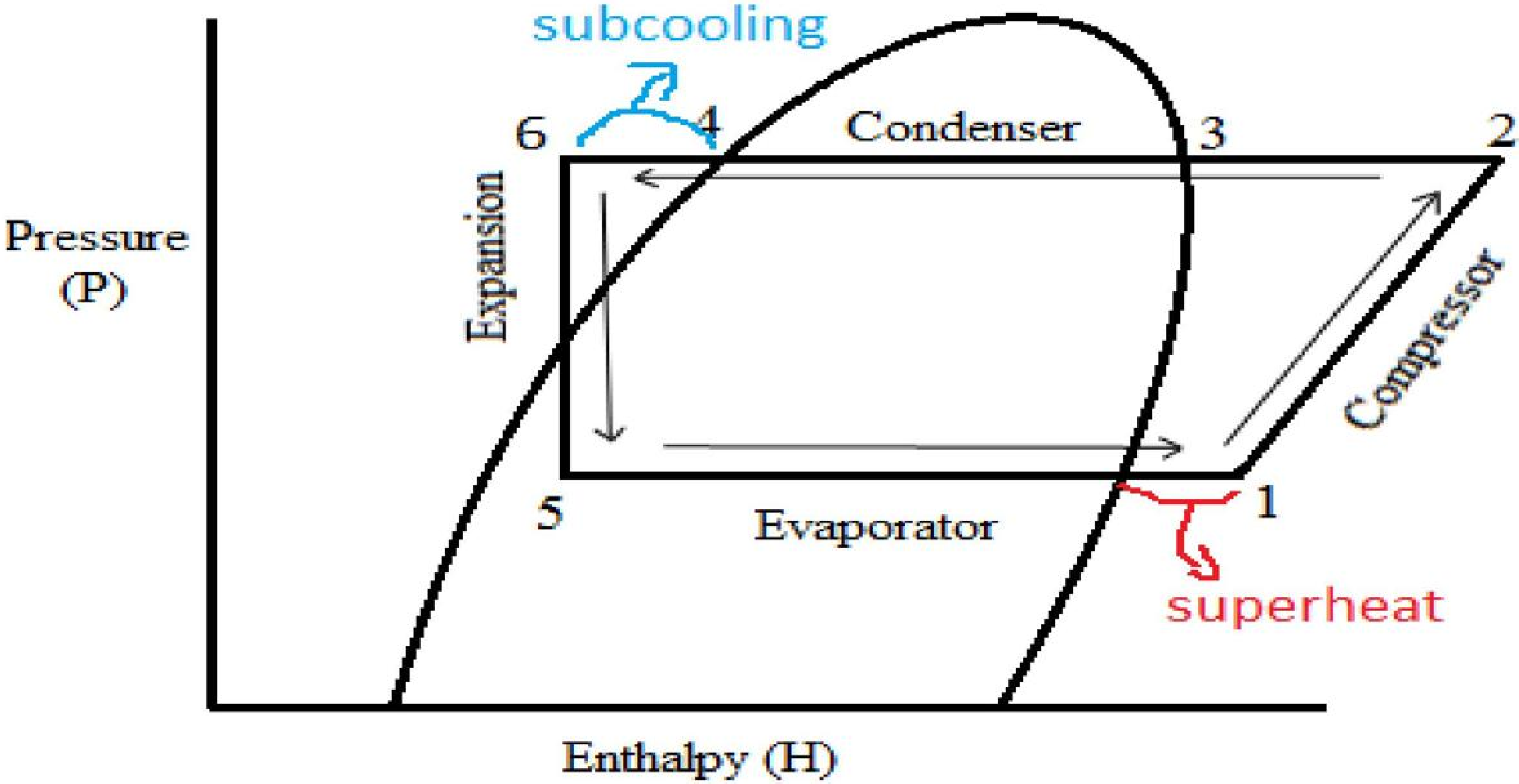
❑ Consequently, the quantity of vapor which enters the compressor is decreased by superheating. Thus we see that the capacity of the system of refrigeration increases with superheating of the vapor, and simultaneously the refrigeration capacity is decreased with the decrease in density during superheating. The result of these two opposite trends must be observed to establish whether or not the refrigerating capacity of a system is increased by superheating. However, superheating ensures total evaporation of the liquid refrigerant before it goes into the compressor.

❑ Since the increase in work is more as compared to increase in refrigerating effect, therefore overall effect of superheating is to give a low value of C.O.P.

- Subcooling in refrigeration implies cooling the refrigerant in liquid state, at uniform pressure, to a temperature that is less than the saturation temperature, which corresponds to condenser pressure.
- **Subcooling is defined as the amount of heat removed from a liquid below its condensing point**.
- Effect of sub-cooling:
- Sub-cooling is the process of cooling the liquid refrigerant below the condensing temperature for a given pressure. As is evident from the figure the effect of sub-cooling is to increase the refrigerating effect.
- Thus sub-cooling results in increase of C.O.P provided that no further energy has to be spent to obtain the extra cold coolant required.

Cont….

- P-V Diagraph & T-S diagraph



Psychrometry

Introduction

Thepsychrometry is that branch of engineering science, which deals with the study of moist air i.e. dry air mixed with water vapour or humidity. It also includes the study of behaviour of dry air and water vapour mixture under various sets of conditions.

Though the earth's atmosphere is a mixture of gases including nitrogen (N_2), oxygen(O_2), argon (Ar) and carbon dioxide (CO_2), yet for the purpose of psychrometry, it is considered to be a mixture of dry air and water vapour only.

Phychrometric Terms

1. **Dry air:**
   - The dry air is nothing but the air without moisture or water vapour.
   - The pure dry air is a mixture of a number of gases such as nitrogen, oxygen carbon dioxide hydrogen, argon, neon, helium etc. But the nitrogen and oxygen have the major portion of the combination.

The dry air is considered to have the composition as given in the following table:

Composition of dry air

S.No	Constituent	By volume	By mass	Molecular mass
1.	Nitrogen(N_2)	78.03%	75.47%	28
2.	Oxygen(O_2)	20.99%	23.19%	32
3.	Argon (Ar)	0.94%	1.29%	40
4.	Carbon-	0.03%	0.05%	44
5.	dioxide(CO_2)	0.01%	---	2
	Hydrogen (H_2)			

The molecular mass of dry air is taken as 28.966 and the gas constant of air (R_a) is equal to 0.287 kJ/kg K or 287 J/kg K

The molecular mass of water vapour is taken as 18.016 and he gas constant for water vapour (R_v) is equal to 0.461 kJ/kg K or 461 J/kg K

Note:

(a) The pure dry air does not ordinarily, exist in nature because it always contain some water vapour.

(b) The term air, wherever used in his text, means dry air containing moisture in the vapour form

(c) Both dry air and water vapour can be considered as perfect gases because both exist in the atmosphere at low pressure. Thus all the perfect gas terms can be applied to them individually.

(d) The density of dry air is taken as 1.29.kg/m^3 at pressure 1.0135 bar or 101.35 kN/m^2 and at temperature 0^{o}C(273K)

2. **Moist air:** It is a mixture of dry air and water vapour.
   The amount of water vapour, present in the air, depends upon the absolute pressure and temperature of the mixture.

Moist air

↙ ↘

Dry air (Fixed part) — Water vapour (Variable part)

3. **Saturated air:** It is a mixture of dry air and water vapour, when the air has diffused the maximum amount of water vapour into it.

   The water vapours, usually, occur in the form of superheated steam as an invisible gas, However, when the saturated air is cooled, the water vapour in the air starts condensing, and the same may be visible in the form of moist, fog or condensation on cold surfaces.

4. **Dry bulb temperature:**
   - It is the temperature of air measured by a thermometer, when it is not affected by the moisture present in the air.
   - The dry bulb temperature is genially denoted by t_d or t_{db}

5. **Wet bulb temperature:**
   - It is the temperature of air measured by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air.
   - Such a thermometer is called wet bulb thermometer. The web bulb temperature is generally denoted by t_w or t_{wb}

6. **Wet bulb depression:**
   - It is the difference between dry bulb temperature (DBT) and wet bulb temperature (WBT) at any point.

     Wet bulb depression = DBT-WBT
   - The value of wet bulb depression is zero when the air becomes saturated.
   - The wet bulb depression indicates relative humidity of the air.

7. **Dew point temperature:**
   - It is the temperature at which the moisture (water vapour) present in air begins to condense when the air is cooled.
   - **Note**: For saturated air, the dry bulb temperature, we bulb temperature and dew point temperature is same.

Additional reading:

In other words, the dew point temperature is the saturation temperature (t_{sat}) corresponding to the partial pressure of water vapour (p_v) It is, usually, denoted by t_{dp} since p_v is very small, therefore the saturation temperature by water vapour at p_v is also low (easy than the atmospheric or dry bulb temperature) Thus the water vapour in air exists in the superheated site and the moist air containing moisture in such a form (i.e. superheated site) is said to be unsaturated air. This condition is shown by water vapour (p_v) is equal to the saturation pressure (p_s) the water vapour is in dry condition and the air

will be saturated air.
Diagram

If a sample of unsaturated air, containing superheated water vapour, is cooed at constant pressure, the partial pressure (p_v) of each constituent remains constant until the water vapour reaches the saturated state as shown by point B in Fig. At this point B, the first drop of dew will be formed and hence the temperature at point B is called dew point temperature. Further cooling will cause condensation of water vapour.

From the above we see that the dew point temperature. Wet bulb temperature and dew point temperature is same

8. **Dew point depression:** It is the difference between the dry bulb temperature and dew point temperature of air. DPD = DBT - DPT
9. **Psychrometer:** There are many types of psychrometer, but the sling psychrometer as shown in fig. is widely used.

   It consists of a dry bulb thermometer and a wet bulb thermometer mounted side by side in a perceive case that is attached to a handle by a swivel connectionso that the case that is attached to a handle by a swivel connectionso that the case can be easy rotated. The dry bulb thermometer is directly exposed to air and measures the actual temperature of the air. The bulb of the wet bulb thermometer is covered by a wick thoroughly wetted by distilled water. The temperature measured by this wick covered bulb of a thermometer is the temperature of liquid water in the wick and is called wet bulbtemperature

The sling psychrometer is rotated in the air for approximately one minute after which the readings from both the thermometers are taken. This process is repeated several times to assure that the lowest possible we bulb temperature is recorded.

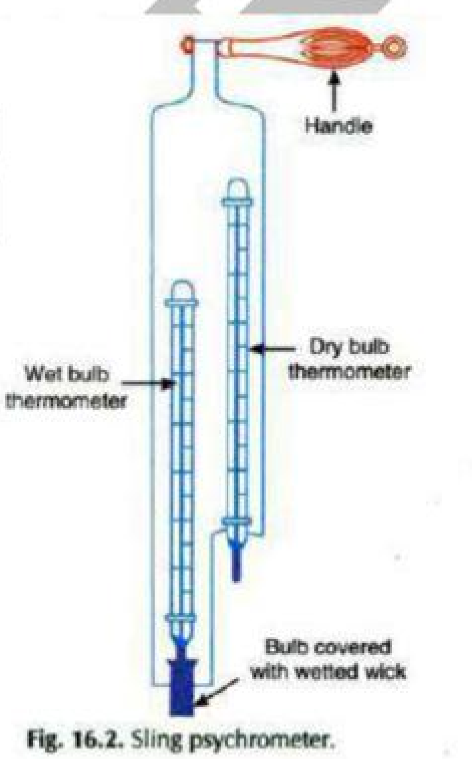


Fig. 16.2. Sling psychrometer.


Digital psychrometer.

Dalton's Law of Partial Pressures

- It states, 'The total pressure exerted by the mixture of air and water vapour is equal to the sum of the pressures,which each constituent would exert, if it occupied the same space by itself' ***or***
- The total pressure exerted by air and water vapour mixture is equal to the barometric pressure.

Mathematically, barometric pressure of the mixture,

$$p_b = p_a + p_v$$

Where p_a =Partial pressure of dry air, and

p_v = Partial pressure of water vapour.

Properties of Moist Air

1. **Humidity or Specific humidity or humidity ratio or moisture constant:**

It is the mass of water vapour present in 1 kg of dry air (in the air-vapour mixture) and is generally expressed in gram/kg of dry air.

It may also be defined as the ratio of mass of water vapour to the mass of dry air in a given volume of the air-vapour mixture.

$$W = \frac{\text{Mass of wate rvapour}}{\text{mass of dry air}} = \frac{m_v}{m_a} \quad \frac{kgwv}{kgda}$$

$\therefore$ Humidity ratio,

$$W = \frac{m_v}{m_a} = \frac{R_a p_v}{R_v p_a}$$

$$= \frac{0.287 \times p_v}{0.461 \times p_a} = 0.622 \times \frac{p_v}{p_a} = 0.622 \times \frac{p_v}{p_b - p_v} \qquad \because R_a = 0.287 kJ/kg \quad R_v = 0.461 kJ/kg\ K$$

$$....(\because p_b = p_a + p_v)$$

Consider unsaturated air containing superheated vapour at dry bulb temperature t_d and partial pressure p_v as shown by point A on the $T-s$ diagram in Fig. 16.3 If water is added into this unsaturated air, the water will evaporate which will increase the moisture content (specific humidity) of the air and the partial pressure p_v increases. This will continue unit the water vapour becomes saturated at that temperature, as show in by point C in Fig. 16.3 and there will be more evaporation of water. The partial pressure p_v increases to the saturation pressure p_s and it is maximum partial pressure of water vapour at temperature t_d. The air containing moisture in such a state (point C) is called saturated

Diagram

For saturated air (i.e., when the air is holding maximum amount of water vapour), the humidity ratio or maximum specific humidity.

$$W_s = W_{\max} = 0.622 \times \frac{p_s}{p_b - p_s}$$

Where $p_s =$ Partial pressure of air corresponding to saturation temperature (i.e. dry bulb temperature t_d)

2. **Degree of saturation or percentage humidity:**
   - Degree of saturation is defined as the ratio of specific humidity of moist air to specific humidity of saturated air at the same temperature..

   - In other words, degree of saturation is the ratio of actual mass of water vapour in a unit mass of dry air to the mass of water vapour in the same mass of dry air when it is saturated at the same temperature (dry bulb temperature)

It is, usually, denoted by μ. Mathematically, degree of saturation.

$$\mu = \frac{W}{W_s} = \frac{\text{Specific humidity of moist air}}{\text{Specific humidity of saturated air}} = \frac{\dfrac{0.622 p_v}{p_b - p_v}}{\dfrac{0.622 p_s}{p_b - p_s}} = \frac{p_v}{p_s}\left(\frac{p_b - p_s}{p_b - p_v}\right) = \frac{p_v}{p_s}\left[\frac{1 - \dfrac{p_s}{p_b}}{1 - \dfrac{p_v}{p_b}}\right]$$

Notes:

a) The partial pressure of saturated air (p_s) is obtained from the steam tables corresponding to dry bulb temperature t_d.

b) If the relative humidity $\phi = p_v / p_s$ is equal to zero, then the humidity ratio W=O, i.e. for dry air, $\mu = 0$

c) If the relative humidity $\phi = p_v / p_s$ is equal to 1, then $W = W_s$ and $\mu = 1$. Thus μ varies between 0 and 1

3. **Relative humidity(ϕ):**

   Relative humidity is the ratio of actual mass of water vapour (m_v) in (a given volume of) moist air to the mass of water vapour (m_s) under saturated condition in the same volume at the same temperature.

   It is usually denoted by ϕ Mathematically, relative humidity

$$\phi = \frac{m_v}{m_s} = \frac{\text{mass of water vapour in a given volume}}{\text{Saturated mass of water vapour in same volume of temperature}}$$

Let

p_v, v_v, T_v, m_v and R_v = Pressure, volume, temperature, mass and gas constant respectively for water vapour in actual conditions, and

p_s, v_s, T_s, m_s and R_s = Corresponding values for water vapour in saturated air,

We know that,

$p_v v_v = m_v R_v T_v$ for water vapour in actual conditions ...(i)

$p_s v_s = m_s R_s T_s$ for water vapour in saturated air ....(ii)

$\therefore$ From equation (i) and (ii) relative humidity

$$\phi = \frac{m_v}{m_s} = \frac{p_v}{p_s},$$

Sinceaccording to the definitions, $v_v = v_s$

and $T_v = T_s$

Also $R_v = R_s = 0461 kJ/kg\,K$

Thus, the relative humidity may also be defined as the ratio of actual partial pressure of water vapour in moist air at a given temperature (dry bulb temperature) to the saturation pressure of water vapour (or partial pressure of water vapour in saturated air) at the same temperature.

The relative humidity may also be obtained as discussed below.

We know that degree of saturation

$$\mu = \frac{p_v}{p_s}\left[\frac{1-\frac{p_s}{p_b}}{1-\frac{p_v}{p_b}}\right] = \phi\left[\frac{1-\frac{p_s}{p_b}}{1-\phi\times\frac{p_s}{p_b}}\right] \quad \ldots\left(\because \phi = \frac{p_v}{p_s}\right)$$

$$\phi = \frac{\mu}{1-(1-\mu)\frac{p_s}{p_b}}$$

Note:

- For saturated air, the relative humidity is 100%
- Relative humidity plays an important role in the comfort air conditioning and industrial air conditioning compared to the specific humidity.

4. **Pressure of water vapour:** According to Carrier's equation, the partial pressure of water vapour,

$$pv = p_w - \frac{(p_b - p_w)(t_d - tw)}{1544 - 1.44 t_w}$$

Where p_w = saturation pressure corresponding to wet bulb temperature (from steam tables)

p_b ==Barometric pressure

t_d = Dry bulb temperature, and

t_w = Wet bulb temperature

4. **Vapour density or absolute humidity:** Vapour density or absolute humidity is the mass of water vapour present in $1m^3$ of dry air

It is generally expressed in terms of gram per cubic-metre of dry air (g/m^3 of dry air).

It is also expressed in terms of grains per cubic metre of dry air.

Mathematically one kg of water vapour is equal to grains.

Let v_v = volume of water vapour in m^3/kg of dry air at its partial pressure,

v_a = volume of dry air in m^3/kg of dry air at its partial pressure,

ρ_v = density of water vapour in kg/m^3 corresponding to its partial pressure and dry bulb temperature t_d and

p_a = Density of dry air in kg/m^3 of dry air

We know that mass of water vapour, $m_v = v_v \rho_v$ ....(i)

and mass of dry air, $m_a = v_a \rho_a$ .....(ii)

Dividing equation (i) by equation (ii),

$$\frac{m_v}{m_a} = \frac{v_v \rho_v}{v_a \rho_a} = \frac{\rho_v}{\rho_a} \quad \because v_a = v_v$$

Therefore, humidity ratio,

$$W = \frac{m_v}{m_a} = \frac{\rho_v}{\rho_a}$$

$$\Rightarrow \quad \rho_v = W \rho_a$$

$$= W \frac{p_a}{R_a T_d} \qquad \because\ p_a v_a = m_a R_a T_d \Rightarrow p_a \times \frac{1}{\rho_a} = R_a T_d \quad \Rightarrow \quad \rho_a = \frac{p_a}{R_a T_d}$$

$$= \frac{W(p_b - p_v)}{R_a T_d} \qquad p_b = p_a + p_v \qquad \because v_a = \frac{1}{\rho_a} \ \ and \ \ m_a = 1kg$$

Where p_a = pressure of air in kN/m^2

R_a = Gas constant for air = 0.287 kJ/kg K and

T_d = Dry bulb temperature in K

Enthalpy (Total heat) of Moist Air

The enthalpy of moist air is numerically equal to the enthalpy of dry air plus the enthalpy of water vapour associated with dry air.

Enthalpy of moist air = Enthalpy of dry air + Enthalpy of water vapour

Let us consider one kg of dry air.

Enthalpy of 1 kg of dry air, $h_a = c_{pa} t_d$

Where c_{pa} = Specific heat of dry air which is normally taken as 1.005 kJ/kg K, and

t_d = Dry bulb temperature

Enthalpy of water vapour associated with 1kg of dry air, $h_v = w h_s$ ....(ii)

Where W = Mass of water vapour 1 kg of dry air (i.e. specific humidity), and

h_s = Enthalpy of water vapour per kg of dry air at dew point temperature $\left(t_{dp}\right)$

If the moist air is superheated,

then the enthalpy of water vapour $= W\, c_{ps}\left(t_d - t_{dp}\right)$ ...(iii)

Where

c_{ps} = Specific heat of superheated water vapour, normally taken as 1.9 kJ/kg K,and

$t_d - t_{dp}$ = degree of superheat of the water vapour

$\therefore$ Total enthalpy of superheated water vapour

$$h = c_{pa}t_d + W\,h_s + W\,c_{ps}\left(t_d - t_{dp}\right)$$

$$= c_{pa}t_d + W\left[h_{fdp} + h_{fgdp} + c_{pd}\left(t_d - t_{dp}\right)\right] \quad ....\left(\because h_s = h_{fdp} + h_{fsdp}\right)$$

$$= c_{pa}t_d + W\left[4.2t_{dp} + h_{fgdp} + c_{ps}\left(t_d - t_{dp}\right)\right] \quad ....\left(\because h_{fdp} = 4.2t_{dp}\right)$$

$$= c_{pa}t_d + 4.2W\,t_{dp} + W\,h_{fgdp} + W\ c_{ps}d_d - W\,c_{ps}t\,dp$$

$$= \left(c_{pa} + W\,c_{ps}\right)t_d + W\left[h_{fgdp} + t_{dp}\left(4.2 - c_{ps}\right)\right]$$

$$= \left(c_{pa} + W\,c_{ps}\right)td + W\left[h_{fgdp} + t_{dp}\left(4.2 - 1.9\right)\right]$$

$$= \left(c_{pa} + W_{cps}\right)t_d + W\left[h_{fgdp} + 2.3t_{dp}\right]$$

The term $\left(c_{pa} + W\,c_{ps}\right)$ is called humid specific heat $\left(c_{pm}\right)$. It is the specific heat or heat capacity of moist air, i.e (1+W) kg/kg of dry air. At low temperature of air conditioning range the value of W is very small. The general value of humid specific heat in air conditioning range is taken as 1.022 kJ/kg K

$$\therefore \qquad h = 1.022t_d + W\left(h_{fgdp} + 2.3t_{dp}\right)kJ$$

Where h_{fgdp} = Latent heat of vaporisation of water corresponding to dew point temperature (from steam tables)

Note: In a general used form, h = 1.005t +w(2500+1.88t)

C_{pa} = 1.005 KJ/kg-k

h_{fg} = 2500 KJ/kg

C_{pv} = 1.88

Enthalpy of water vapour associated with 1kg of dry air, $h_v = wh_s$ ....(ii)

Where W = Mass of water vapour 1 kg of dry air (i.e. specific humidity), and

h_s = Enthalpy of water vapour per kg of dry air at dew point temperature (t_{dp})

If the moist air is superheated,

then the enthalpy of water vapour $= W\,c_{ps}\left(t_d - t_{dp}\right)$ ...(iii)

Where

c_{ps} = Specific heat of superheated water vapour, normally taken as 1.9 kJ/kg K,and

$t_d - t_{dp}$ = degree of superheat of the water vapour

$\therefore$ Total enthalpy of superheated water vapour

$$h = c_{pa}t_d + W\,h_s + W\,c_{ps}\left(t_d - t_{dp}\right)$$

$$= c_{pa}t_d + W\left[h_{fdp} + h_{fgdp} + c_{pd}\left(t_d - t_{dp}\right)\right] \qquad ....\left(\because h_s = h_{fdp} + h_{fsdp}\right)$$

$$= c_{pa}t_d + W\left[4.2t_{dp} + h_{fgdp} + c_{ps}\left(t_d - t_{dp}\right)\right] \qquad ....\left(\because h_{fdp} = 4.2t_{dp}\right)$$

$$= c_{pa}t_d + 4.2W\,t_{dp} + W\,h_{fgdp} + W\ c_{ps}d_d - W\,c_{ps}t\,dp$$

$$= \left(c_{pa} + W\,c_{ps}\right)t_d + W\left[h_{fgdp} + t_{dp}\left(4.2 - c_{ps}\right)\right]$$

$$= \left(c_{pa} + W\,c_{ps}\right)td + W\left[h_{fgdp} + t_{dp}\left(4.2 - 1.9\right)\right]$$

$$= \left(c_{pa} + W_{cps}\right)t_d + W\left[h_{fgdp} + 2.3t_{dp}\right]$$

The term $\left(c_{pa} + W\,c_{ps}\right)$ is called humid specific heat $\left(c_{pm}\right)$. It is the specific heat or heat capacity of moist air, i.e (1+W) kg/kg of dry air. At low temperature of air conditioning range the value of W is very small. The general value of humid specific heat in air conditioning range is taken as 1.022 kJ/kg K

$$\therefore \qquad h = 1.022t_d + W\left(h_{fgdp} + 2.3t_{dp}\right)kJ$$

Where h_{fgdp} = Latent heat of vaporisation of water corresponding to dew point temperature (from steam tables)

Note: In a general used form, h = 1.005t +w(2500+1.88t)

C_{pa} = 1.005 KJ/kg-k

h_{fg} = 2500 KJ/kg

C_{pv} = 1.88

Thermodynamic Wet bulb Temperature or Adiabatic Saturation Temperature

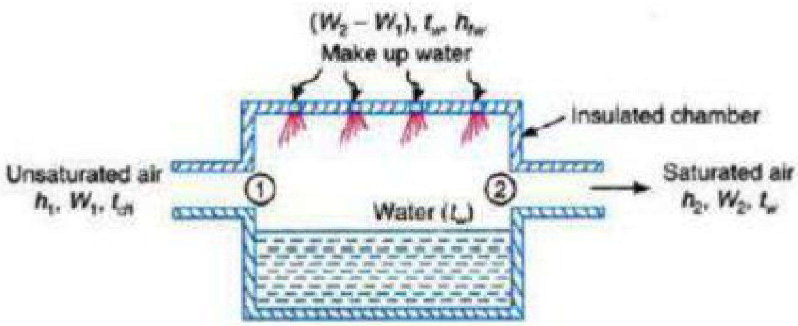
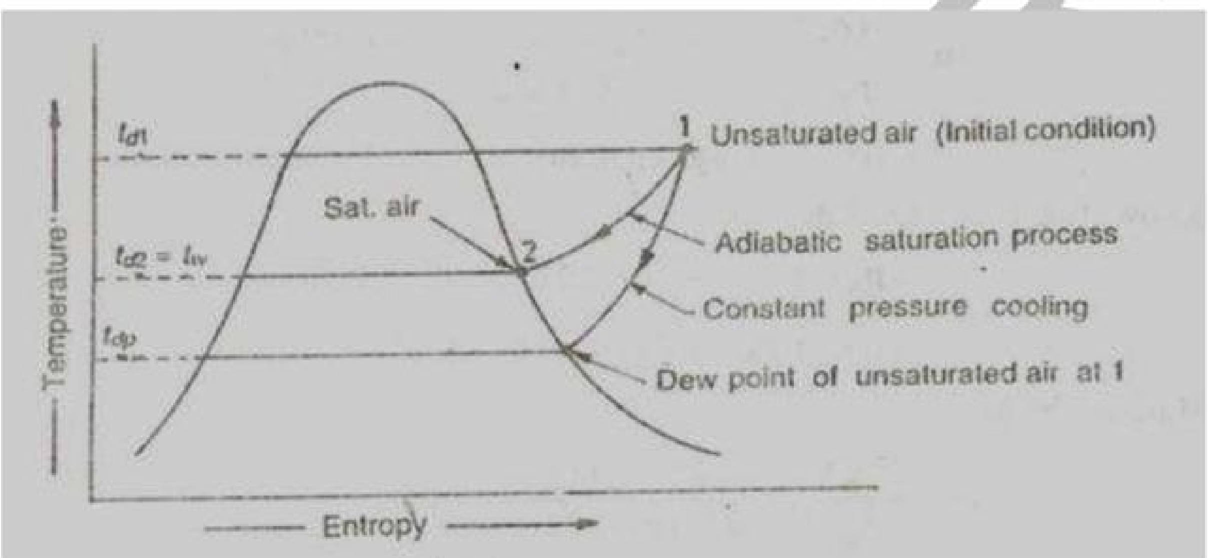


Fig. 16.4. Adiabatic saturation of air.



Psychometric Chart

It is a graphical representation of the various thermodynamic properties of moist air.

Note: The psychrometric chart is very useful for finding out the properties of air (which are required in the field of air conditioning) and eliminate lot of calculations. There is a slight variation in the charts prepaid by different air – conditioning manufactures but basically they are all alike. The psychrometric chart is normally draw for standard atmospheric pressure of 760mmof Hg (or 1.01325 bar)

- In a psychrometric chart, dry bulb temperature is taken as abscissa and specific humidity i.e. moisture contents as ordinate, as shown in Fig.
- The saturation curve represents 100% relative humidity at various dry bulb temperatures. It also represents the wet bulb and dew point temperatures.

Though the psychrometricchart has a number of details, yet the following lines are important from the subject point of view.

1. **Dry bulb temperature lines:** The dry bulb temperature lines are vertical and uniformly spaced as shown in Fig.

Generally the temperature range of these lines on psychrometric chart is from -6° C to 45° C. The dry bulb temperature lines are drawn with difference of every 5°C and up to the saturation curves as shown in the figure the values of dry bulb temperatures are also shown on the saturation curve.

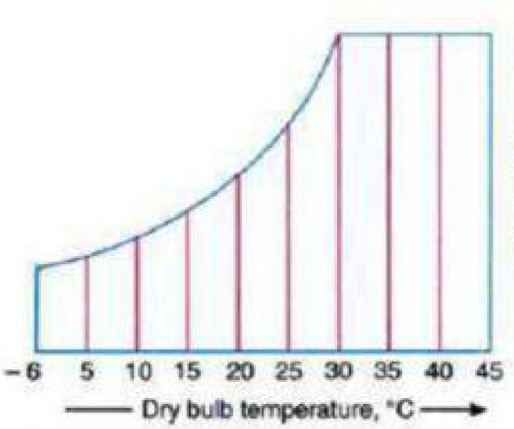


Fig. 16.7. Dry bulb temperature lines.

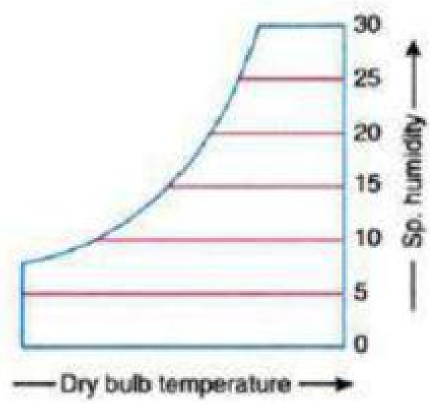


Fig. 16.8. Specific humidity lines.

2. **Specific humidity or moisture content lines:** The specific humidity (moisture content) lines are horizontal and are uniformly spaced as show in Fig.
   Generally, moisture content range of these lines on psychrometric chart is from 0 to 30g/kg of dry air (or from 0 to 0.30kg/kg of dry air)The moisture content lines are drawn with a difference of every 1g (or 0.001 kg) and up to the saturation curve as shown in the fig.

3. **Dew point temperature lines:** The dew point temperature lines are horizontal and non-uniformly spaced as shown in Fig. At any point on the saturation curve, the dry bulb and dew point temperature are equal.
   The values of dew point temperature are generally given along the saturation curve of the chart as shown in the figure.

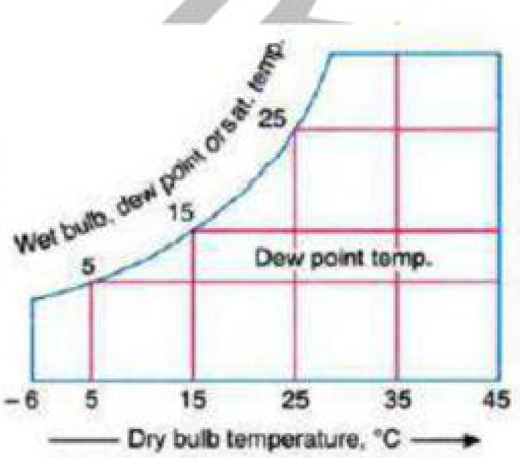


Fig. 16.9. Dew point temperature lines.

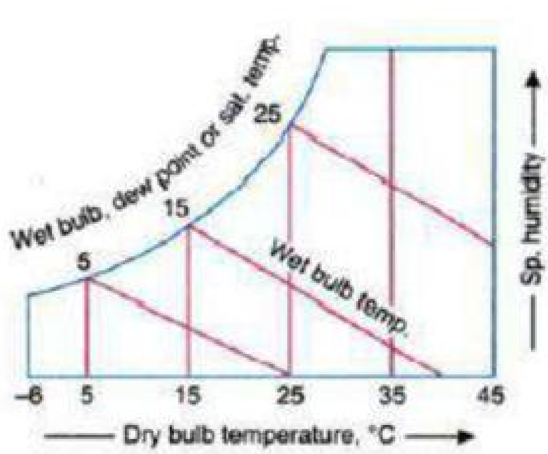
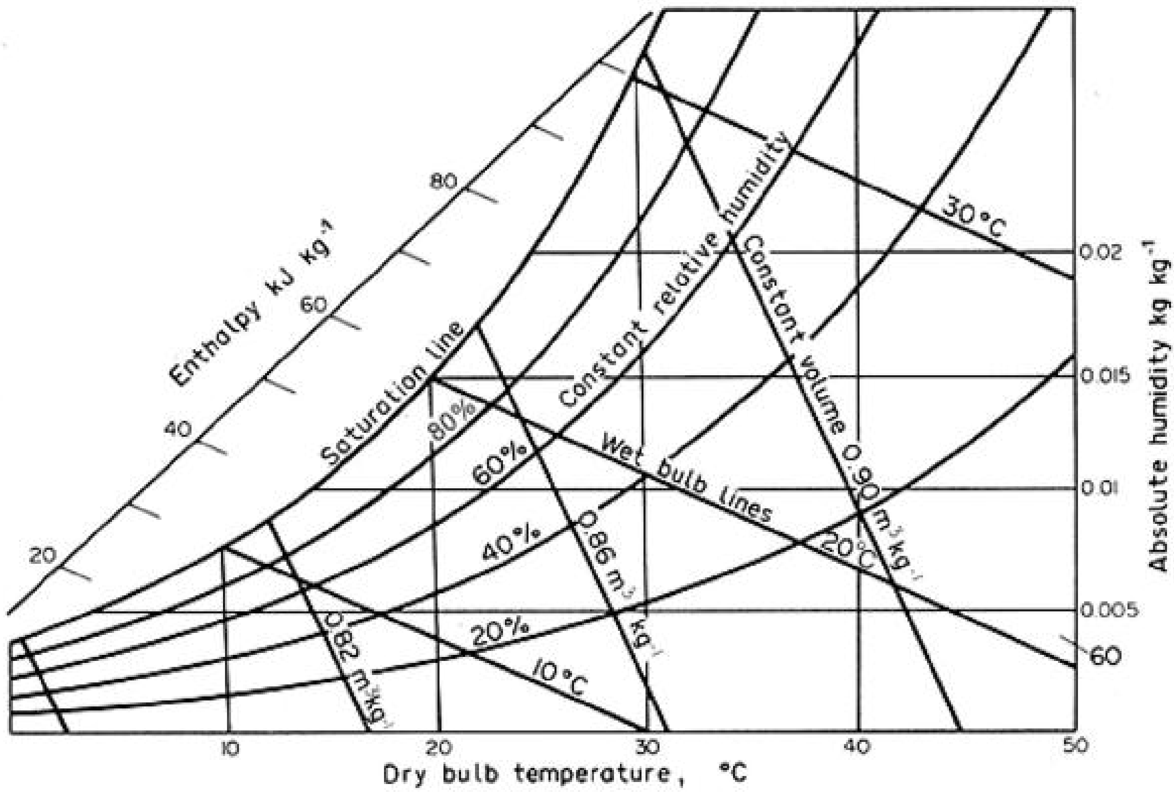


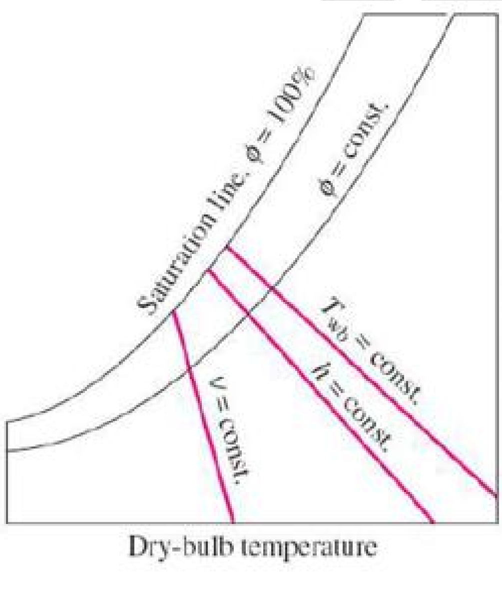
Fig. 16.10. Wet bulb temperature lines.

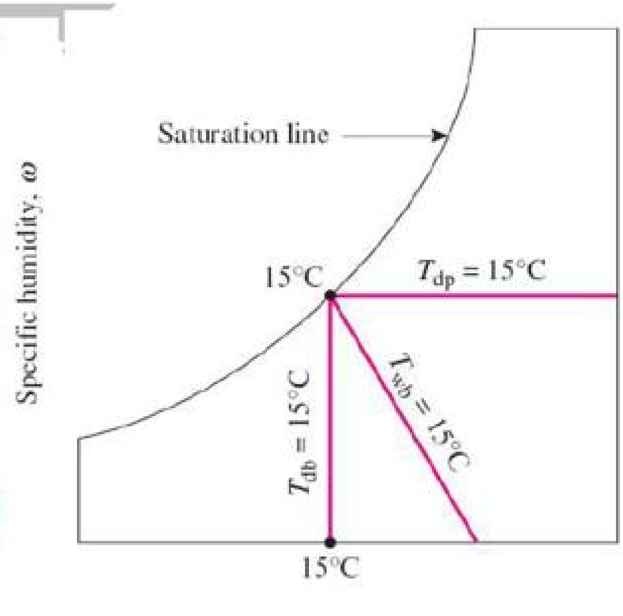
3. **Wet bulb temperature lines:** The wet bulb temperature lines are inclined straight lines and non-uniformly speed as shown in Fig.
   At any point on the saturation curve the dry bulb and wet bulb temperature are equal.

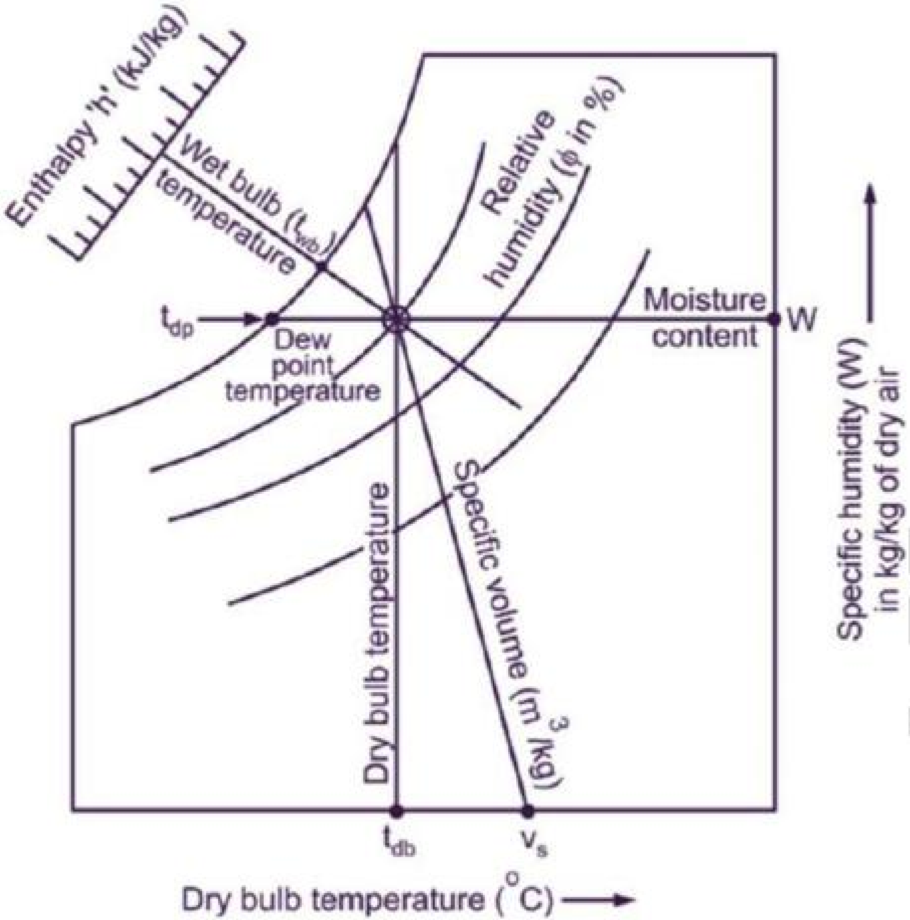
8. Relative humidity line:

The relative humidity lines are curved lines and follow the saturation curve. Generally, these lines are drawn with values 10%,20%,30% etc. and upto 100%. The saturation curve represents 100% relative humidity lines are generally given along the lines themselves as shown in Fig.





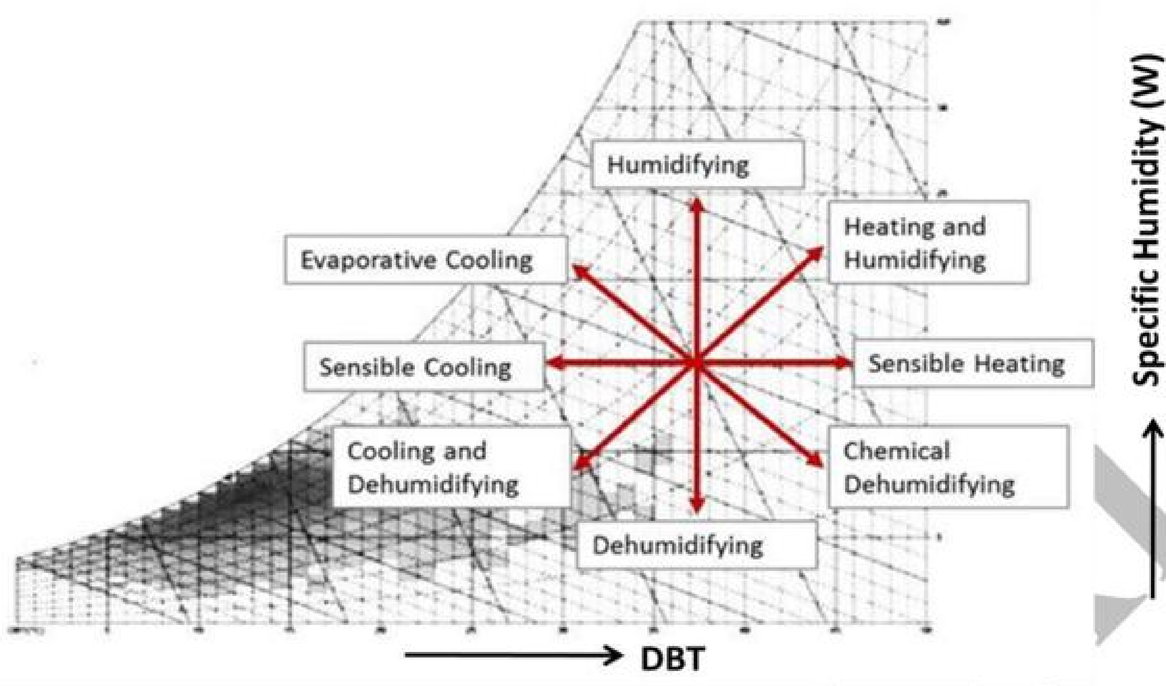




Psychrometric Processes

The various psychrometric processes involved in air conditioning to vary the psychrometric properties of air according to the requirement are follows:

i. Sensible heating
ii. Sensible cooling
iii. Humidification and dehumidification
iv. Cooling and adiabatic humidification,
v. Cooling and humidification by water injection
vi. Heating and humidification
vii. Humidification by steam injection,
viii. Adiabatic chemical dehumidification,
ix. Adiabatic mixing of air streams.

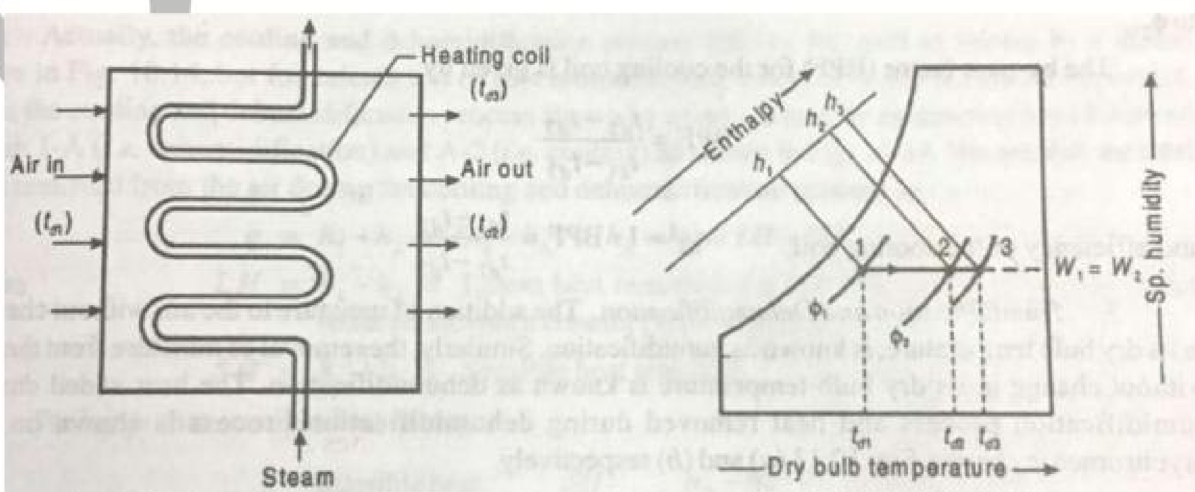


Sensible Heating

- The heating of air, at constant specific humidity 'W' (without any change in its specific humidity) is known as sensible heating.
- Let air at temperature t_{d1} passes over a heating coil of temperature t_{d3} as shown in fig. It may be noted that the temperature of air leaving the heating coil (t_{d2}) will be less than t_{d3}.

The process of sensible heating, on the psychrometric chart, is shown by a horizontal line 1-2 extending from left to right as shown. The point 3 represents the surface temperature of the heating coil

- It may be noted that the specific humidity during the sensible heating remains constant (i.e. $W_1 = W_2$).
- They dry bulb temperature increases from t_{d1} to t_{d2} and relative humidity reduces from ϕ_1 to ϕ_2 as shown in fig.



(*a*) Psychrometric process. (*b*) Psychrometric chart.

The heat absorbed by the air during sensible heating may be obtained from the psychrometric chart by the enthalpy difference $(h_2 - h_1)$ as shown in fig.

The amount of heat added during sensible heating may also be obtained from the reaction:

Heat added, $q = h_2 - h_1$

$$= c_{pa}(t_{d2} - t_{d1}) + W c_{ps}(t_{d2} - t_{d1})$$

$$= (c_{pa} + W c_{ps})(t_{d2} - t_{d1}) = c_{pm}(t_{d2} - t_{d1})$$

The term $(c_{pa} + W c_{ps})$ is called humid specific heat (c_{pm}) and its value is taken as 1.022 kJ/kg K.

$\therefore$ Heat added, $q = 1.022(t_{d2} - t_{d1}) kJ/kg$

Note: 1. For sensible heating steam or hot water is passed through the heating coil.The heating coil may be electric resistance coil

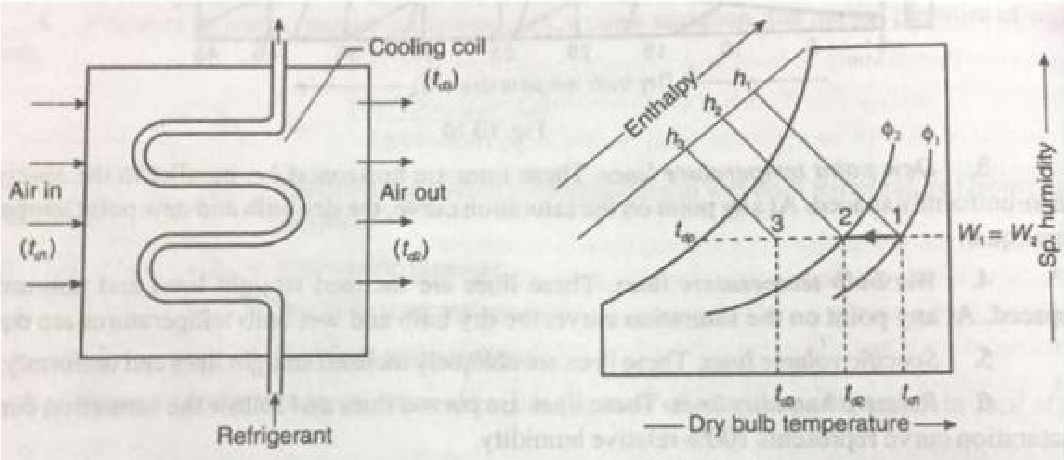
2. The sensible heating of moist air can be done to any desired temperature.

Sensible Cooling

- The cooing of air, at constant specific humidity 'W' (without any change in its specific humidity), is known as sensible cooing.
- Let air at temperature t_{d1} passes over a cooing coil of temperature t_{d3} as shown in a) It may be noted that the temperature of air leaving the cooling coil (t_{d2}) will be more than t_{d3}.

The process of sensible cooing, on the psychrometric chart, is shown by a horizontal line 1-2 extending from right to left as shown in fig. The point 3 represents the surface temperature of the cooling coil.

- It may be noted that the specific humidity during the sensible cooing remains constant $(i.e.\ W_1 = W_2)$.
- The dry but temperature reduces from t_{d1} to t_{d2} and relative humidity increases from ϕ_1 to ϕ_2 as shown in Fig.



(*a*) Psychrometric process. (*b*) Psychrometric chart.

The heat rejected by air during sensible cooing may be obtained from the psychrometric chart by the enthalpy difference $(h_1 - h_2)$ as shown in fig.

The amount of heat rejected during sensible cooing may also be obtained from the reaction.

Heat rejected, $q = h_1 - h_2$

$$= c_{pa}(t_{d1} - t_{d2}) = W c_{ps}(t_{d1} - t_{d2})$$

$$= (c_{pa} + W c_{ps}) = (t_{d1} - t_{d2}) = c_{pm}(t_{d1} - t_{d2})$$

The term $(c_{pa} - W c_{ps})$ iscalled humid specific heat (c_{pm})and its value is taken as 1.022 kJ/kg K.

$\therefore$ Heat rejected, $q = 1.022(t_{d1} - t_{d2})$ kJ/kg

For air conditioning purposes, the sensible het per minute is given as

$$SH = m_a c_{pm} \Delta t = v \rho c_{pm} \Delta t \; kJ/\min \qquad ...(\because m = v\rho)$$

Where v= rate of dry air flowing in m^3/min

ρ = Density of moist air at 27°C and 50% reactive humidity

=1.2kg /m^3 of dry air

c_{pm} = Humid specific heat = 1.022 kJ/kg.K, ad

$\Delta t = t_{d1} - t_{d2}$=Differences of dry bulb temperature between the entering and leaving conditions of air in °C

Substituting the values of ρ and c_{pm} in the above expression, we get

$$SH = v \times 1.2 \times 1.022 \times \Delta t = 1.2264 v \times \Delta t \; kJ/\min$$

$$\frac{1.2264 \times \Delta t}{60} = 0.02044 v \times \Delta t \; kJ/s \text{ or } kW$$

Note: 1. Four sensible cooing, the cooling coil may have refrigerant cooling water or coo gas flowing through it

2. The sensible cooing can be done onlyupto the dew point temperature $\left(t_{dp}\right)$ as shown in 16.17(b) The cooing below this temperaturewill result the condensation of moisture

By-Pass factor of heating and Cooling Coil

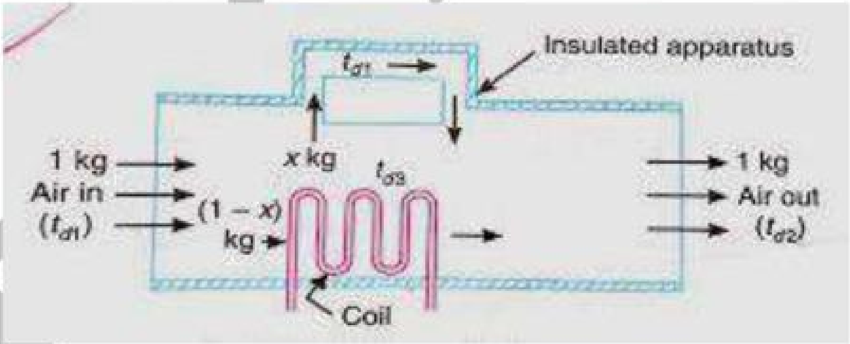
The dry bulb temperature of air leaving the apparatus should be equal to that of the heating/cooling coil. But it is not so.

The temperature t_{d1} is passed over the coil having its temperature (i.e. coil surface temperature) t_{d3} as shown in fig

A little consideration will show that when air passes over a coil, some of it (say x kg) just by-passes unaffected while the remaining (1-x) kg comes in direct contact with the coil. This by pass process of air is measured in terms of a by pass factor. The amount of tail that by-passes or the by-pass factor depends upon the following factors.

1. The number of fins provided in a unit length i.e. the pitch of the cooling coil fins:
2. The number of rows in a coil in the direction of flow; and
3. The velocity of flow of air

It may be noted that the by-pass factor of a cooing coil decreases with decreases in fin spacing and increase in number of rows



Balancing the enthalpies, we get

$$x c_{pm} t_{d1} + (1-x) c_{pm} t_{d3}$$
$$= 1 \times c_{pm} t_{d2}$$

or $\quad x\left(t_{d3}-t_{d1}\right)=t_{d3}-t_{d2}$

$\therefore \quad x=\dfrac{t_{d3}-t_{d2}}{t_{d3}-t_{d1}}$

Where x is called the by-pass factor of the coil and is generally written as BPF. Therefore, by-pass factor for heating coil.

$$BPF=\frac{t_{d3}-t_{d2}}{t_{d3}-t_{d1}}$$

Similarly, by-pass factor for cooing coil,

$$BPF = \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}}$$

The by-pass factor for heating or cooling coil may also be obtained as discussed below.

Efficiency of Heating and Cooling Coils

The term (1-BPF) is known as efficiency of coil or contact factor.

∴ Efficiency of the heating coil.

$$\eta_H = 1 - BPF = 1 - \frac{t_{d_3} - t_{d2}}{t_{d3} - t_{d1}} = \frac{t_{d2} - t_{d1}}{t_{d3} - t_{d1}}$$

Similarly, efficiency of the cooing coil.

$$\eta_C = 1 - \frac{t_{d_2} - t_{d3}}{t_{d1} - t_{d3}} = \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}}$$

Humidification and Dehumidification

The addition of moisture to the air, without change in its dry bulb temperature is known as humidification, Similarly, removal of moisture from the air, without change in its dry bulb temperature is known as dehumidification. The heat added during humidification process and heat removed during dehumidification process is shown on the psychrometric chart in Fig. (a) and (b) respectively.

It may be noted that in humidification, the relative humidity increases from ϕ_1 *to* ϕ_2 and specific humidity also increases from W_1 to W_2 as shown in Fig. Similarity

, in dehumidification from W_1 to W_2 as shown in fig

Diagram

It may be noted that in humidification change in enthalpy is shown by the intercept $(h_2 - h_1)$ on the psychrometric chart. Since the dry bulb temperature of air during the humidification remains constant, therefore its sensible het also remains constant. It is thus obvious, that the change in enthalpy per kg of dry air due to the increased moisture content equal to $(W_2 - W_1)$kg per kg of dry air is considered to cause a latent heat transfer (LH) Mathematically,

$$LH = (h_2 - h_1) = h_{fg}(W_2 - W_1)$$

Where h_{fg} is the latent heat of vaporisation at dry bulb temperature (t_{d1})

Methods of obtaining Humidification and Dehumidification

The humidification is achieved either by supplying of spraying steam or hot water or cod water into the air. The humidification may be obtained by the following two methods

1. Direct method: In this method, the water is sprayed in a highly atomised state into the room be air-conditioned. The method of obtaining humidification is not very effective.

2. Indirect method: In this method, the water is introduced into the air in the air-conditioning plant, with the hep of an air washer, as shown This conditioned air is then supplied to the room to be air-conditioned. The air washer humidification may be accomplished in the following three ways.

a)by using re-circulated spray water without prior heating of air

b) by pre-heating the air and then washing it with re-circulated water, and

c) by using heated spray water.

The dehumidification may be accomplished with the hep of an air-washer or by using chemicals. In the air-washer system, the outside or entering air is cooed below its dew point temperature so that it losses moisture by condensation. The moisture removal is also accomplished when the spray water is chilled water and its temperature is lower than the dew point temperature of the entering air, Since the air leaving the air washer has its dry bulb temperature much below the desired temperature in the room, therefore a heating coil is paced after the air-washer. The dehumidification may also be achieved by using chemicals which have the capacity to absorb moisture in them. Two types of chemicals known as absorbents (such as calcium chloride) and adsorbents (such as silica gel and activated alumina) are commonly used for this purpose

Sensible Heat Factor

As a matter of a fact, the heat added during a psychrometric process may be split up into sensible heat and latent heat. The ratio of the *sensible heat to the total heat is known as sensible heat factor (briefly written as SHF) or sensible heat ratio (briefly written as SHR) Mathematically

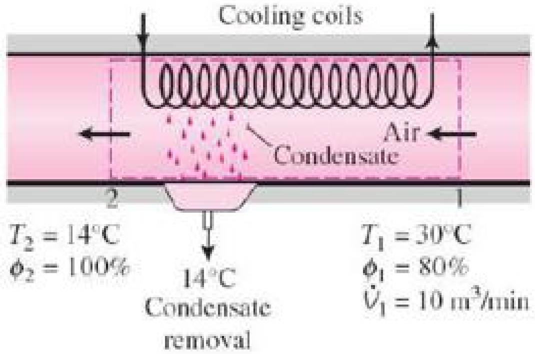
$$SHF = \frac{Sensible\,heat}{Total\,heat} = \frac{SH}{SH + H}$$

SH = Sensible heat, and

LH = Latent heat

Cooling and Dehumidification

This process is generally used in summer air conditioning to cool and dehumidify the air. The air is passed over a cooling coil or through a cold water spray. In this process, the dry bulb temperature as well as the specific humidity of air decreases. The final relative humidity of the air is generally higher than that of the entering air. The dehumidification of air is only possible when the effective surface temperature of the cooling coil (i.e. t_{d4}) is leas than the dew point temperature of the air entering the coil (i.e. t_{dp1}) The effective surface temperature of the coi is known as apparatus dew point (briefly written as ADP) The cooling and dehumidification process is shown in



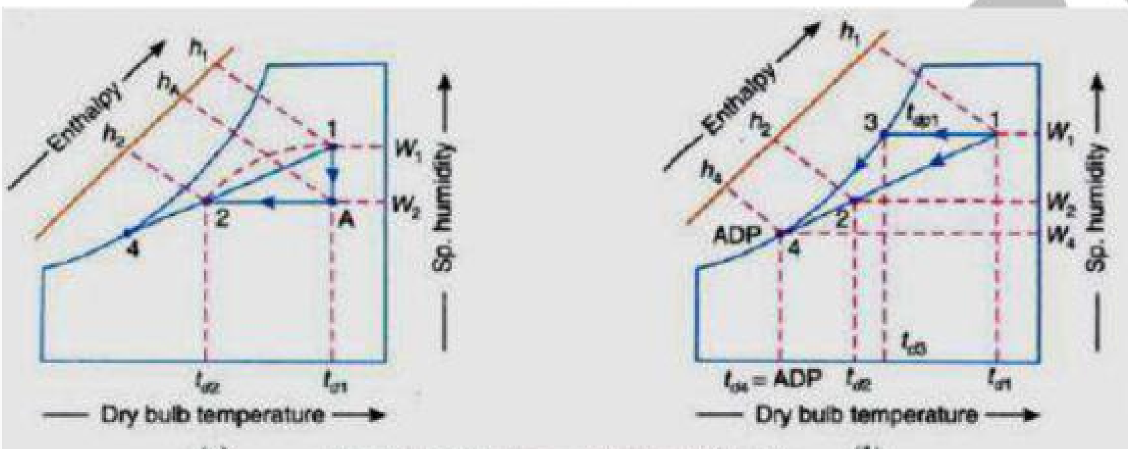


Fig. 16.29. Cooling and dehumidification.

Let t_{d1} = Dry bulb temperature of the air entering the coil

t_{d1} = Dew point temperature of the entering air = t_{d3} and

t_{d4} = Effective surface temperature or ADP of the coil.

Under ideal conditions, the dry bulb temperature of the air leaving the cooing coil(i.e. t_{d4}) should be equal to the surface temperature of the cooling coil (i.e. ADP) but it is never possible due to inefficiency of the cooling coil. Therefore, the resulting condition of air coming out of the coil is shown by a point 2 on the straight in joining the points 1 and 4. The by – pass factor in this case is given by

$$BPF = \frac{td2 - t_{d4}}{t_{d1} - t_{d4}} = \frac{t_{d2} - ADP}{t_{d1} - ADP}$$

Also $BPF = \dfrac{W2 - W4}{W_1 - W_4} = \dfrac{h_4 - h_2}{h_1 - h_2}$

Actually, the cooling and dehumidification process follows the path as shown by a dotted curve in but for the calculationof psychrometric properties, only end points are important. Thus the cooling and dehumidification process shown by a in 1-2 may be assumed to have followed a path 1-A(i.e.dehumidification) and A-2(i.e. cooling)as shown in Fig. We see that the total heat removed from the air during the cooling and dehumidification process is

$$q = h_1 - h_2 = (h_1 - hA) + (h_A - h_2) = LH + SH$$

$LH = h_1 - h_A =$ Latent heat removed due to condensation of vapour of the reduced moisture content $(W_1 + W_2)$ and

$SH = h_A - h_2 =$ sensible heat removed

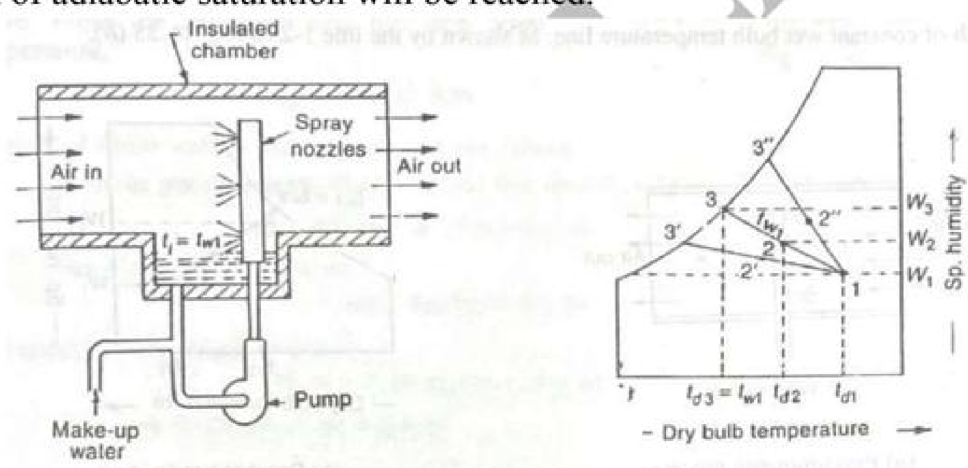
We know that sensible heat factor,

$$SHF = \frac{Sensibe\,heat}{Total\,heat} = \frac{SH}{LH + SH} = \frac{h_A - h_2}{h_1 - h_5}$$

Note: The line 1-4(i.e. the line joining the point of entering air and the apparatus dew point) in Fig.

Cooling with Adiabatic Humidification

When the air is passed through an insulated camber, as shown in Fig. having sprays of water (known as air washer) maintained at a temperature (t_l) higher tan the dew point temperature of entering air (t_{dp1}), but lower than its dry bulb temperature $(t_{d1})$of entering air (or equal to the wet bulb temperature of the entering air(t_{w1})then the air is said to be cooed and humidified since no heat is supplied or rejected from the spray water as the same water is re-circulated again and again, therefore, in this case, a condition of adiabatic saturation will be reached.



(*a*) Psychrometric process. (*b*) Psychrometric chart.

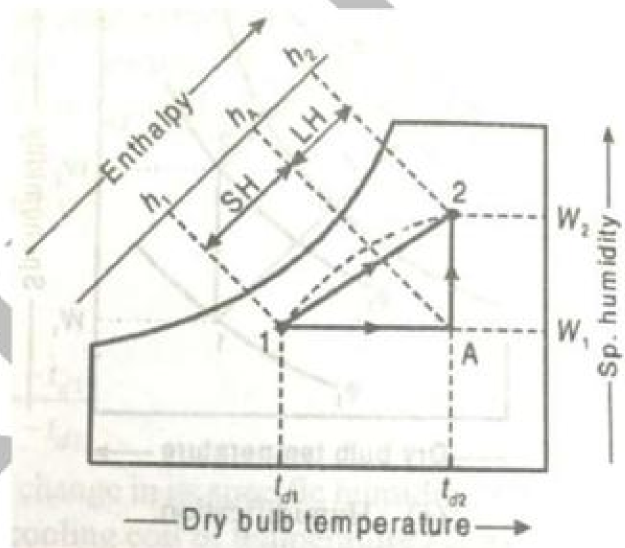
Fig. 16.34. Cooling with adiabatic humidification.

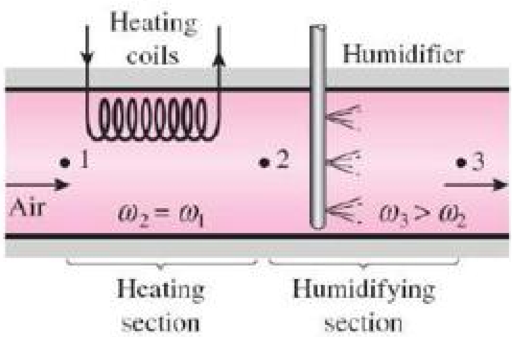
The temperature of spray water will reach the thermodynamic wet bulb temperature of the air entering the spray water. This process is shown in by line1-3 on the psychrometric chart as shown fig(b) and follows the path along the constant we bulb tempera rue line or constant enthalpy line

Cooling and Humidification by Water Injection (Evaporative Cooling) Let water at temperature t_l is injected into the flowing stream of dry air as shown in Fig. The final condition of air depends upon the amount of water evaporation. When the water is injected at a temperature equal to the wet bulb temperature of the entering air (t_{w1}), then the process follows the path of constant wet bulb temperature line, as shown by the line

Heating and Humidification

The process is generally used in winter air conditioning tow arm and humidify the air. It is the reverse process of cooling and dehumidification. When air is passed through a humidifier having spray water temperature higher than the dry bulb temperature of the entering air, the unsaturated air will reach the condition of saturation and thus the air becomes hot. The heat of vaporisation of water is absorbed from the spray water itself and hence it gets cooed In this way, the air becomes heated and humidified. The process of heating and humidification is shown by line 1-2 on the psychrometric chart as shown in fig. The air enters at condition 1 and leaves at condition 2. In this process, the dry bulb temperature as well as specific humidity of air increases. The final relative humidity of the air can be lower or higher tan that of the entering air.





Heating and Humidification by stream Injection

The steam is normally injected into the air in order to increase its specific humidity as shown in This process is used for the air conditioning of textile mils where high humidity is to be maintained. The dry bulb temperature of air changes very little during this process, as shown on the psychrometric chart

Let m_s = Mass of steam supplied

m_a = Mass of dry air entering

W_1 = Specific humidity of air entering

W_2 = Specific humidity of air leaving

h_1 = Enthalpy of air entering

h_2 = Enthalpy of air leaving and

h_s = Enthalpy of stream injected into the air

Now for the mass balance,

$$W_2 = W_1 + \frac{m_s}{m_a}$$

And for the heat balance,

$$h_2 = h_1 + \frac{m_s}{m_a} \times h_s = h_1 + (W_2 - W_1) h_s \quad \text{....[From equation (i)]}$$

Heating and Dehumidification – Adiabatic Chemical Dehumidification

This process is mainly used in industrial air conditioning and can also be used for some comfort air conditioning installations requiring either a low relative humidity or low dew point temperature in the room

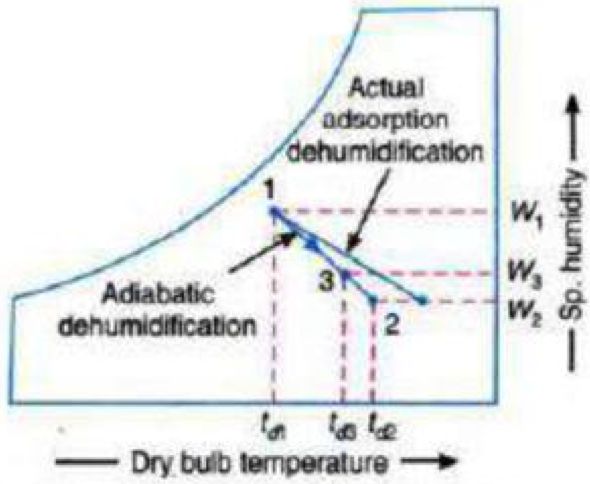


Fig. 16.46. Heating and dehumidification.

In this process, the air is passed over chemicals which have an affinity for moisture. As the air comes in contact with these chemicals, the moisture gets condensed out of the air andgives up its latent heat Due to the condensation, the specific humidity decreases and the heat of condensation supplies sensible heat for heating the air ad thus increasing its dry bulb temperature. The process, which is reverse of adiabatic saturation process, is shown by the line 1-2 on the psychrometric chart as shown in the path followed during the process is along the constant wet bulb temperature line or constant enthalpy line

The effectiveness of efficiency of the dehumidifier is given as

$$\eta_H = \frac{Actual\,increase\,in\,dry\,bulb\,temperature}{Ideal\,increase\,in\,dry\,bulb\,temperature} = \frac{d_{d3} - t_{d1}}{t_{d2} - t_{d1}}$$

Note: 1. In actual practice, the process is accompanied with a release of heat called heat of adsorption, which is very large. Thus the sensible heat gain of air exceeds the loss of latent heat and the process is shown above the constant we bulb temperature in fig.

2. Two types of chemicals used for dehumidification are absorbents and adsorbents. The absorbents are substances which can take up moisture from air and during this process change it chemically, physically or in both respects. These includes water solutions or brines of calcium chloride, lithium chloride, lithium bromide and ethylene glycol. These are used as air dehydrators by spraying or otherwise exposing a large surface of the solution in the air stream.

The absorbents as substances in the solid state which can take up moisture from the air and during this process do not change it chemically or physically. These include silica gel (which is a form of silicon dioxide prepared by mixing fused sodium silicate and sulphuric acid) and activated alumina (which is a porous amorphous form of aluminium oxide)

Adiabatic Mixing of Two Air Streams

When two quantities of air having different enthalpies and different specific humidifies are mixed, the final condition of the air mixture depends upon the masses involved, and on the enthalpy and specific humidity of each of the constituent masses which enter the mixture

Now consider two air streams 1 and 2 mixingadiabatically as shown in fig.

Let m_1 = Mass of air entering at 1

h_1 = Enthalpy of air entering at 1

W_1 = Specific humidity of air entering at 1

m_2, h_2, W_2 = Corresponding values of air, entering at 2, and

m_3, h_3, W_3 = Corresponding values of the mixture leaving at 3

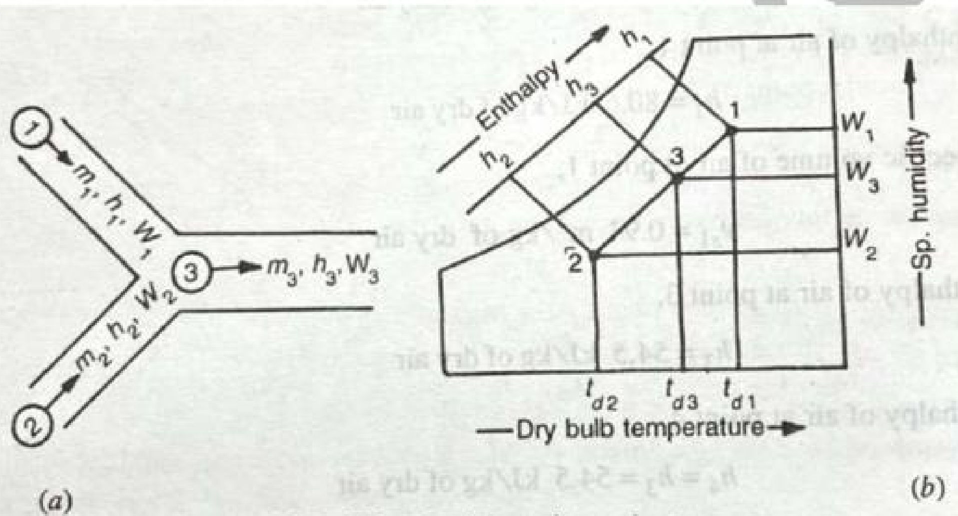


Fig. 16.49. Adiabatic mixing of two air streams.

Assuming no loss of enthalpy and specific humidity during the air mixing process, we have for the mass balance,

$$m_1 + m_2 = m_3 \quad \text{...(i)}$$

For the energy balance

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \quad \text{...(ii)}$$

and for the mass balance of water vapour

$$m_1 W_1 + m_2 W_2 = m_3 W_3 \quad \text{....(iii)}$$

Substituting the value of m_3 from equation (i) in equation (ii),

$$m_1 h_1 + m_2 h_2 = (m_1 + m_2) h_3 = m_1 h_3 + m_2 h_3$$

Or $m_1 h_1 - m_1 h_3 = m_2 h_3 - m_2 h_2$

$$m_1 (h_1 - h_3) = m_2 (h_3 - h_2)$$

$$\therefore \qquad \frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W_3} \qquad \text{...(iv)}$$

Similarly, substituting the value of m_3 from equation (i) in equation (iii), we have

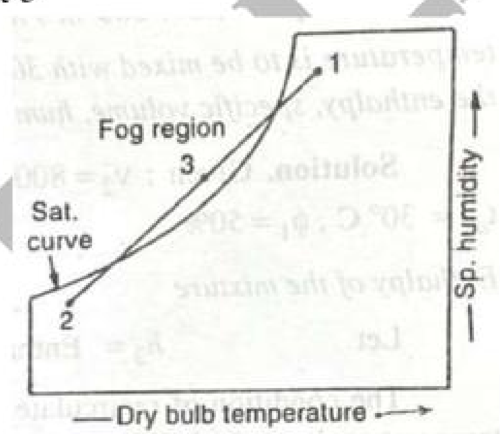
$$\frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W3} \qquad \text{....(v)}$$

Now form equation (iv) and (v)

$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} = \frac{W_3 - W_2}{W_1 - W_3} \qquad \text{....(vi)}$$

The adiabatic mixing process is represented on the psychrometric chart as shown in The final condition of the mixture (point 3) lies on the straight line1-2. The point 3 divides the line 1-2 in the inverse ratio of the mixing masses By calculating the value of W_3 from equation (vi) , the point3 is plotted on the line 1-2

It may be noted that when warm and high humidity air is mixed with cod air, the resulting mixture will be a fog and the final condition (point 3) on the psychrometric chart will lie to the left or above the saturation curve which represents the fog region, as shown in Fig. The temperature of the fog is that of the extended wet bulb line passing through point 3



The fog may also result when steam or a very find water spray is injected into air in a greater quantity than required to saturate the air. Even lesser quantity of steam, it not mixed properly, may result fog.

The fog can be cleared by heating the fog, mixing the fog with warmer unsaturated air or mechanically separating the water droplets from the air.

Air Conditioning System

Introduction

The air conditioning is that branch of engineering science which deals with the study of conditioning of air i.e. supplying and maintaining desirable internal atmospheric conditions for human comfort, irrespective of external conditions. This subject, in its broad sense, also deals with the conditioning of air for industrial purposes, food processing, storage of food and other materials.

Factors affecting comfort air Conditioning

1.Temperature of air: In air conditioning, the control of temperature means the maintenance of any desired temperature within an enclosed space even through the temperature of the outside air is above or below the desired room temperature. This is accomplished either by the addition or removal of heat from the encased space and when demanded. It may be noted that a human being feelsas comfortable when the air is at 21^0Cwith 56% relative humidity.

2. Humidity of air: The control of humidity of air means the decreasing or increasing of moisture contents of air during summer or winter respectively in order to produce comfortable and healthy conditions. The control of humidity is not only necessary for human comfort but it also increases the efficiency of the worker. In genera, for summer air conditioning, the relative humidity should not be less than 60% whereas for winter air conditioning it should not be more than 40%

3. Purity of air: It is an important factor for the comfort of a human body. It has been noticed that people do not feel comfortable when breathing contained air, even if it is within acceptable temperature and humidity ranges. It is thus obvious that proper filtration, cleaning and purification of air is essential to keep it free from dust and other impurities.

4. Motion of air: The motion or circulation of air is another important factor which should be controlled, in order to keep constant temperature throughout the conditioning space, It is therefore, necessary that there should be equi-distribution of air throughout the space to be air conditioning.

Classification of Air Conditioning system

The air conditioning system may be broadly classified as follows;

1. According to the purpose
    (a) Comfort air conditioning system, and
    (b) Industrial air conditioning system
2. According to season of the year
    a) Winter air conditioning system,
    b) Summer air conditioning system, and
    c)Year-round air conditioning system

3. According to the arrangement of equipment

   a) Unitary air conditioning system, and

   b) Central air conditioning system

In this chapter, we shall discuss all the above mentioned air conditioning system, one by one.

Comfort Air conditioning system

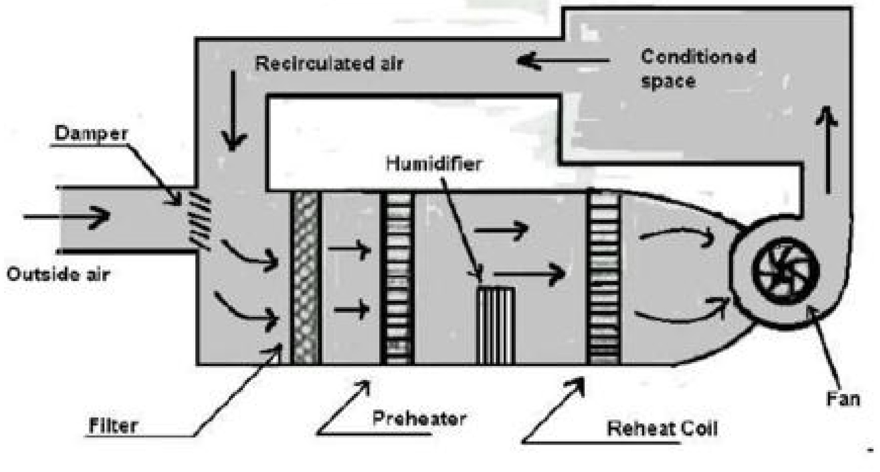
In comfort air conditioning, the air is brought to the required dry bulb temperature and relative humidity for the human heath, comfort and efficiency. If sufficient data of the required condition is not given, then it is assumed to be 21°C dry bulb temperature and 50% relative humidity. The comfort air conditioning may be adopted for homes, offices, shops, restaurants, theatres, hospitals, schools etc.

Industrial Air Conditioning system

It is an important system of air conditioning these days in which the inside dry bulb temperature and relative humidity of the air is kept constant for proper working of the machines and for the proper research and manufacturing processes. Some of the sophisticated electronic and other machines need a particular dry bulb temperature and relative humidity. Sometimes, these machines also require a particular method of psychometric processes. This type of air conditioning system is used in textile mils, paper mills, machine-parts manufacturing pants, too rooms. Photo processing pants etc.

Winter Air conditioning system

In winter air conditioning, the air is heated, which, is generally accompanied by humidification. The schematic arrangement of the system is

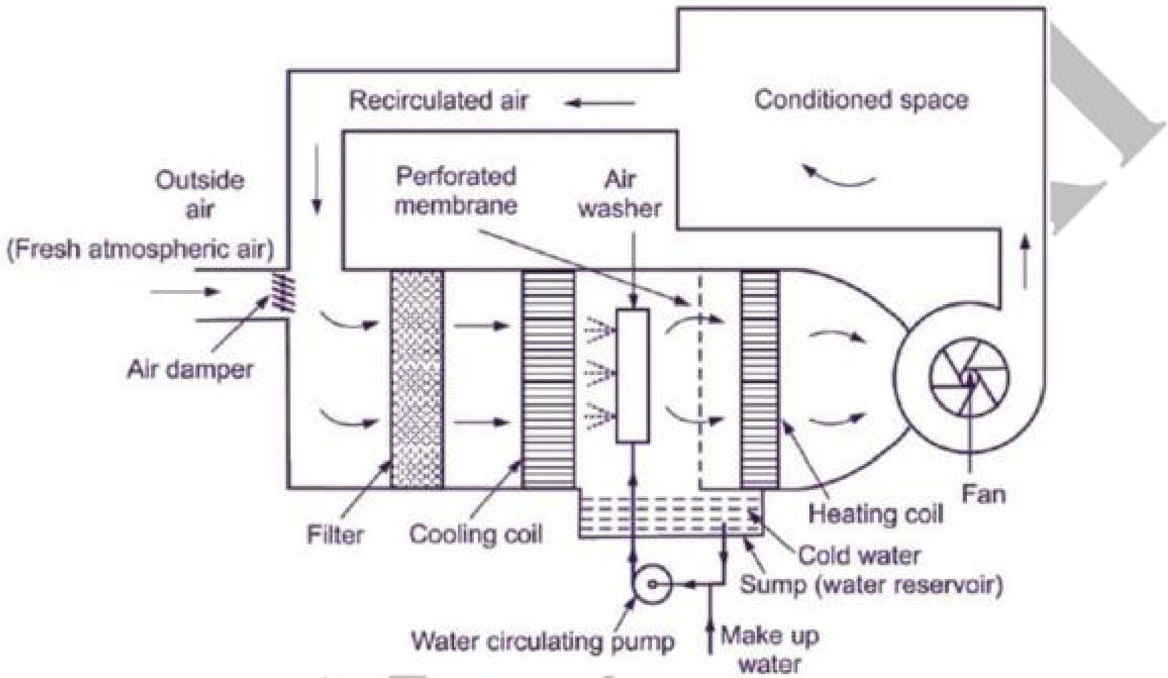


WINTER AIR CONDITIOING SYSTEM

The outside air flows through a damper and mixes up with the recirculated air (which is obtained from the conditioned space). The mixed air passes through a filter to remove dirt, dust and other impurities. The air now passes through a preheat coil in order to prevent the possible freezing of water and to control the evaporation of water in the humidifier. After that, the air is made to pass through a reheat coil to bring the air to the designed dry bulb temperature. Now the conditioned air is supplied to the conditioned space by a fan. From the conditioned space, a part of the used air is exhausted to the atmosphere by the exhaust fans or ventilators. The remaining part of the used air (known as recalculated air) is again conditioned as shown in

Summer Air conditioning System

It is the most important type of air conditioning, in which the air is cooled and generally dehumidified. The schematic arrangement of a typical summer air conditioning system is shown.



The outside air flows through the damper, and mixes up with recalculated air (which is obtained from the conditioned space) the mixed air passes through a fitter to remove dirt, dust and other impurities. The air now passes through a cooling coil. The coil has a temperature much below the required dry bulb temperature of the air in the conditioned space. The cooled air passes through a perforatedmembrane and looses its moisture in the condensed form which is collected in a sump. After that, the air is made to pass through a heating coil which heats up the air slightly. This is done to bring the air to the designed dry bulb temperature and relative humidity.

Now the conditioned air is supplied to the conditioned space by a fan. From the conditioned space, a part of the used air is exhausted to the atmosphere by the exhaust fans or ventilators. The remaining part of the used air (known as recalculated air) is again conditioned as shown in fig The outside air is sucked and made to mix with the recalculated air in order to make up for the loss of conditioned (or used) air through exhaust fans or ventilation from the conditioned space.