Refrigeration and Air Conditioning with Psychrometry

Refrigeration is a process of maintaining low temperature in comparison to surrounding temperature.

"Refrigeration is the process of removing heat from an enclosed space, or from a substance, and rejecting it elsewhere for the primary purpose of lowering the temperature of the enclosed space or substance and then maintaining that lower temperature."

It is usually done with the aid of a mechanical device (e.g. pump/compressor) using a substance (called a refrigerant) which absorbs heat from low temperature (objects/space) and releases heat to elsewhere at high temperature. A refrigerant usually works in two-phase conditions, i.e., liquid and gas, e.g., vapor compression refrigeration system. In some cases, refrigerants remain in single-phase, e.g. air cycle refrigeration.

Current Applications of Refrigeration

- Refrigeration of foodstuffs in homes, restaurants and large storage warehouses.
- Air-conditioning of private homes and public buildings.
- Cold-storage of fruits, vegetables, fish and meats safely for long periods.
- Meats, poultry and fish all must be kept in climate-controlled environments before being sold.
- Refrigeration also helps keep fruits and vegetables edible longer. Dairy products are constantly in need of refrigeration.
- To liquefy gases like oxygen, nitrogen, propane and methane for example.
- In oil refineries, chemical plants, and petrochemical plants, refrigeration is used to maintain certain processes at their required low temperatures.
- Metal workers use refrigeration to temper steel and cutlery.
- In transporting temperature-sensitive foodstuffs and other materials by trucks, trains, airplanes and sea-going vessels.

Types of Refrigeration System

1. Vapor Compression Refrigeration System
2. Vapor Absorption Refrigeration System
3. Vapor Ejection Refrigeration System
4. Air Cycle Refrigeration
5. Vortex Tube Refrigeration
6. Thermo-electric Refrigeration
7. Thermo-acoustics Refrigeration
8. Magnetic Refrigeration
9. Cascade System
10. Cryogenics

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Chemical Refrigerant

A refrigerant is a compound used in a heat cycle that undergoes a phase change from a gas to a liquid and back. The two main uses of refrigerants are refrigerators/freezers and air conditioners.

Refrigerant Properties:

Special Thermodynamic qualities such as suitable boiling point (somewhat below the target temperature), high heat of vaporization, moderate density in liquid form, high density in gaseous form, Non-corrosive, Non-toxic and safe.

Refrigerant Examples:

- Ammonia (boiling point: -33^oC)
- Freon 12 (R-12) (boiling point: -30^oC)
- Freon 22 (R-22) (boiling point: -40^oC)
-Dry ice (CO_2) (boiling point: -73^oC)
- CFC (chlorofluorocarbon)
- HCFC(hydroch1orofluorocarbon)
- HFC (hydrofluorocarbon)

Currently most widely used Refrigerants:

- R-134a (CH_2FCF_3, boiling point: -26^oC)
- R-410a (50% CH_2F_2/50%$CHFCF_3$, boiling point: -48^oC)

Unit of refrigeration

Domestic and commercial refrigerators may be rated in kJ/s, or Btu/h of cooling. Commercial refrigerators in the US are mostly rated in tons of refrigeration, but elsewhere in kW.

One ton of refrigeration capacity can freeze one ***short*** ton of water at 0^oC in 24 hours.

Latent heat of ice (i.e., heat of fusion) = 333.55 kJ/kg

One ***short*** ton = 2000 lb

Heat extracted = (2000)(144)/24 hr = 288000 Btu/24 hr = 12000 Btu/hr = 200 Btu/min

1 ton = [(2000 lb*0.4536 kg/lb)* 333.55 kJ/kg] / (24 hr*3600 sec/hr) = 3.50 kW

<u>1 ton refrigeration = 12000 Btu/hr = 200 Btu/min = 3.50 kJ/s = 3.50 kW.</u>

1 tonne of refrigeration is the rate of heat removal required to freeze a metric ton (i.e., 1000 kg) of water at 0^oC in 24 hours. Based on the heat of fusion being 333.55 kJ/kg,

1 tonne of refrigeration = 13,898 kJ/h = 3.861 kW.

As can be seen, 1 tonne of refrigeration is 10% larger than 1 ton of refrigeration.

Coefficient of Performance (COP)

The Coefficient of Performance for a refrigerator is defined as the ratio of the refrigerating effect (cooling load, Q_R) to the work added (compressor power input, Wc) to the system, i.e. COP = Q_R/ Wc. [Q_R Expressed in ton and Wc in kW]

For a refrigeration system operating between a higher temperature of T_H and a lower temperature of T_L,

COP = $T_L / (T_H - T_L)$ [T_H and T_L are absolute temperatures (degrees kelvin)]

For refrigeration: **COP will be always greater than 1** (typically 2.3 **<** COP< 3.5)

Vapor Compression Refrigeration System

Major Components: (i) Compressor, (ii) Condenser Coil, (iii) Expansion Valve and (iv) Evaporator Coil. Chemical Refrigerants such as R-12, R-22 or R-134a are used to provide refrigeration effect.

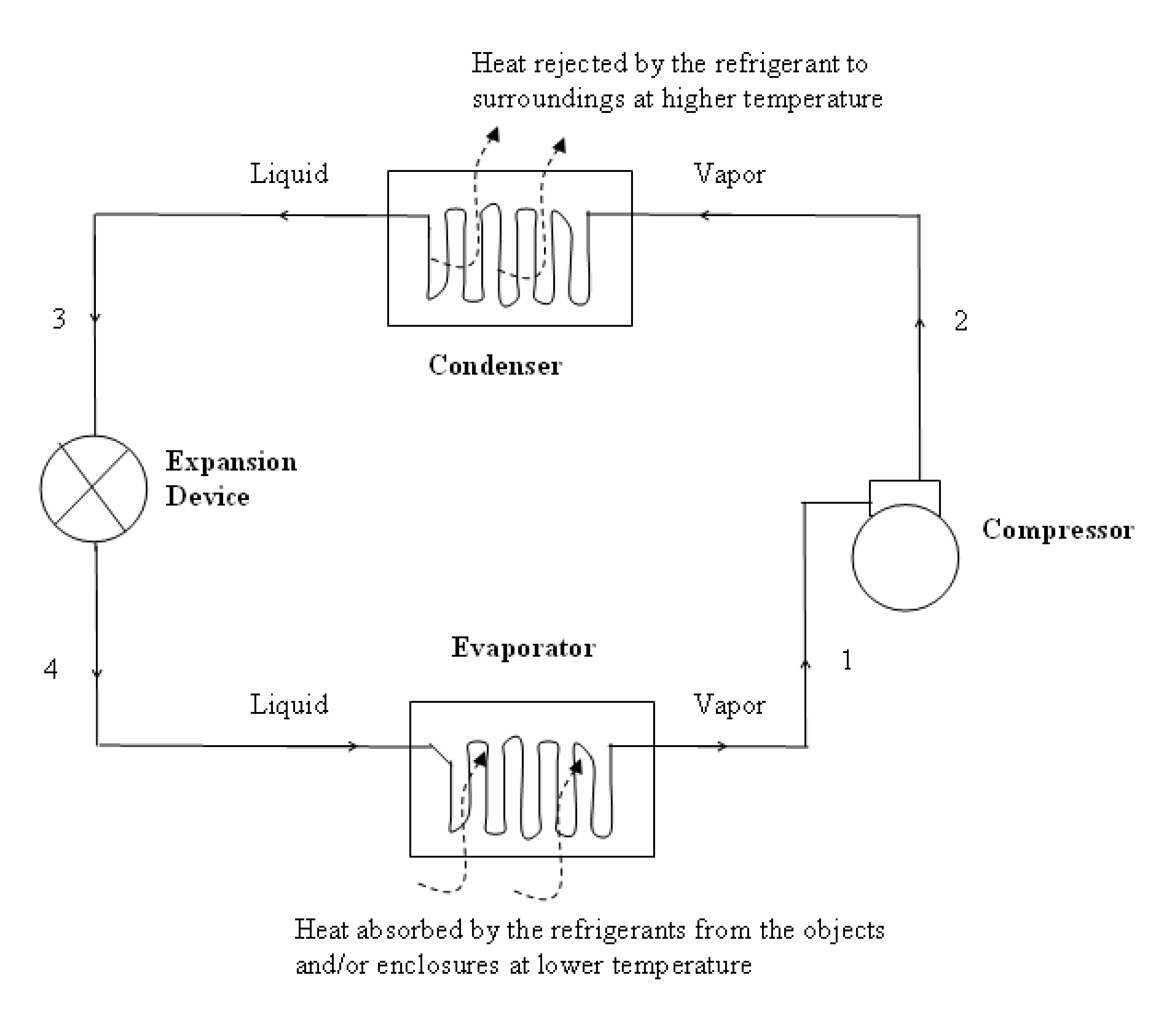


Fig-1: Block/Schematic diagram of vapor compression refrigeration system

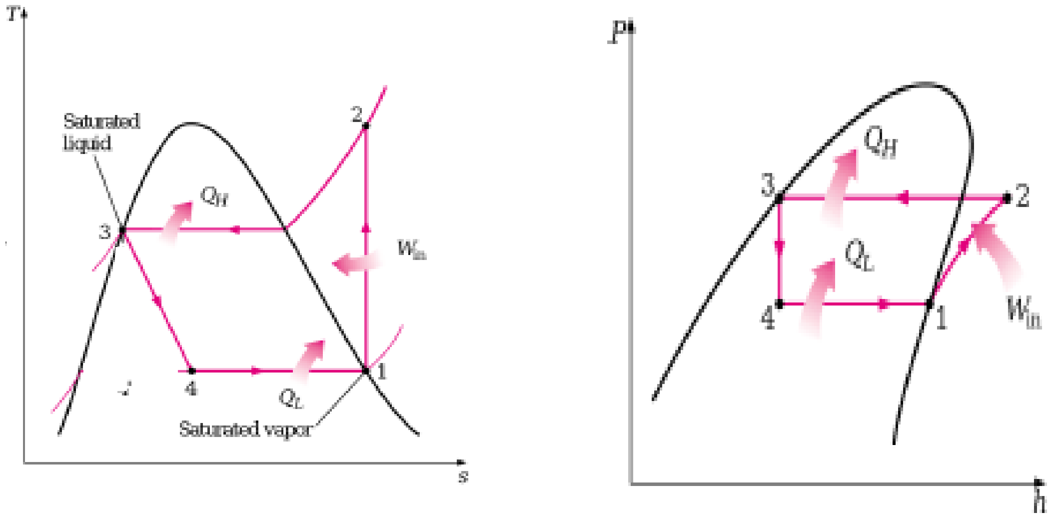
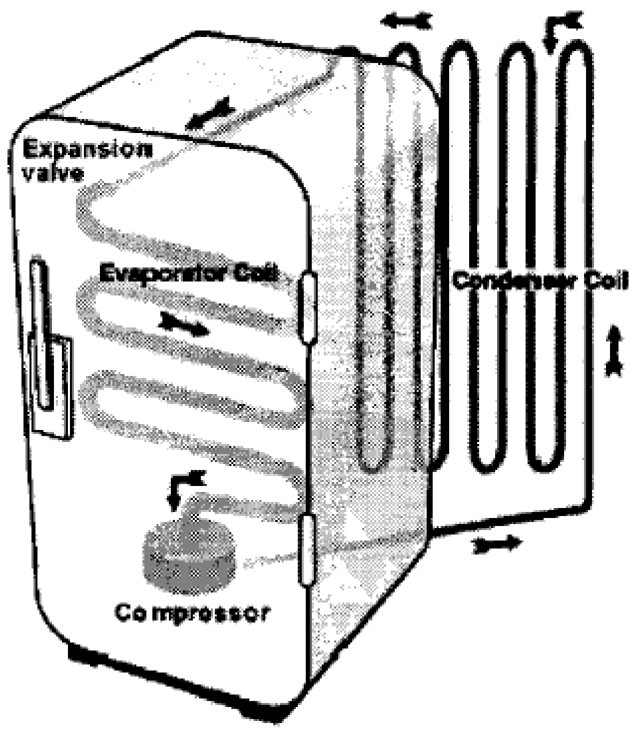


Fig-2: Pressure-enthalpy (p-h) and Temperature-entropy (T-s) of vapor compression refrigeration system (reversed Rankine cycle)

<u>Processes involved in the reversed Rankine cycle:</u>

1-2: isentropic compression,
2-3: constant pressure heat rejection,
3-4: constant enthalpy expansion (throttling),
4-1: constant pressure heat addition.

<u>Brief Description:</u> Refrigerant (R-22 or R134a) vapor from the evaporator is compressed in a compressor and then cooled down to liquid phase in a condenser by exchanging heat with the ambient air. The liquid refrigerant is then throttled using an expansion device to lower its pressure and thus lowering its boiling point. This low pressure liquid refrigerant is then passed through the evaporator coil where it boils and becomes vapor by taking the latent heat from the objects / enclosure surrounding the evaporator coil and the cycle repeats.



Vapor Absorption Refrigeration System

Major Components: (i) Absorber, (ii) Generator (iii) Condenser Coil, (iv) Evaporator Coil, and (v) Pump. Absorbent-Refrigerant pair is used such as water as absorbent and ammonia as refrigerant. LiBr as absorbent, water as refrigerant may also be used.

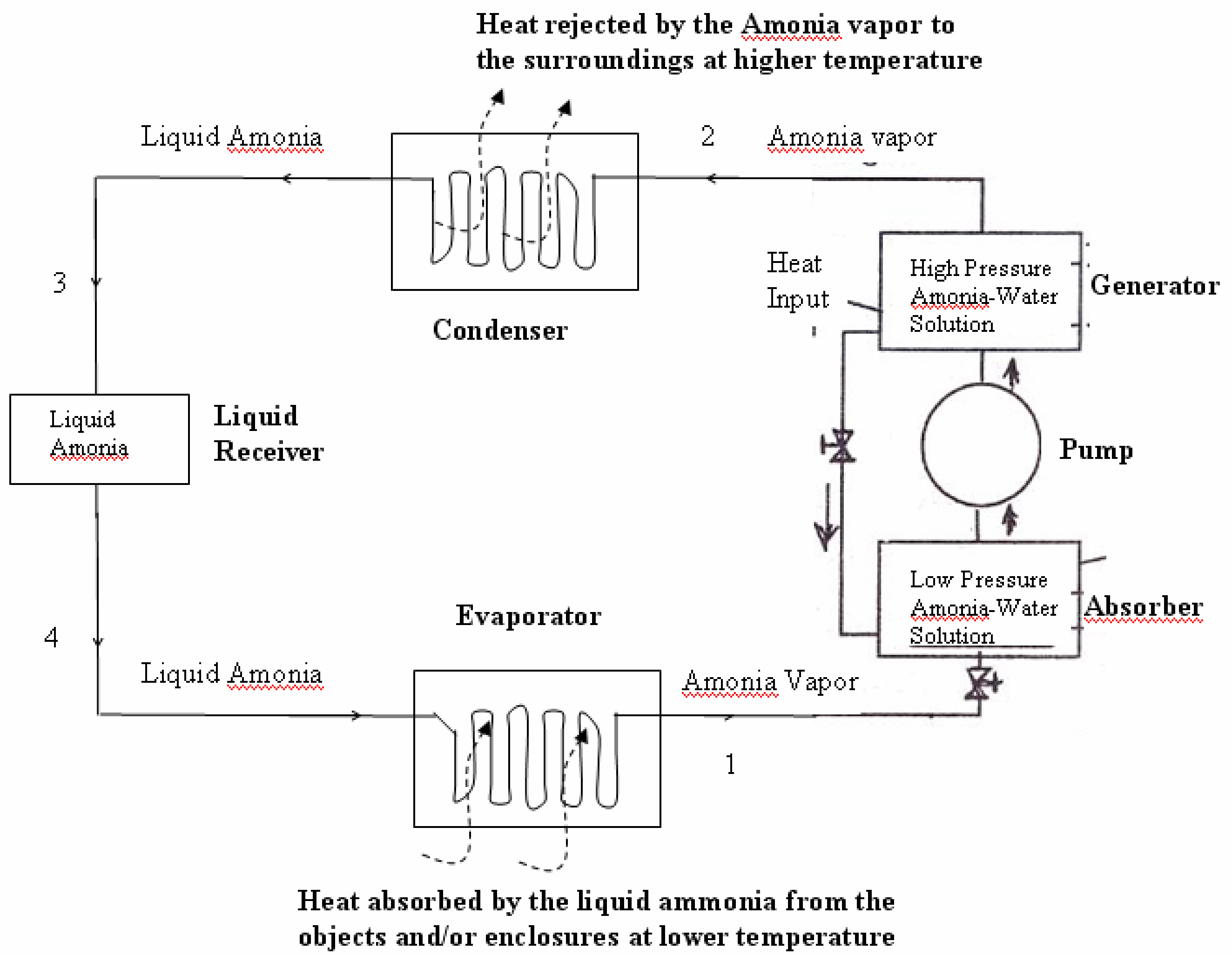


Fig-3: Block/Schematic diagram of vapor absorption refrigeration system

Brief Description: Ammonia gas from the evaporator enters the absorber at point 1. Water in absorber absorbs the ammonia gas. This solution can hold a maximum of 30% ammonia. The pump lifts this rich solution and supplies to generator above where it is heated to generate (separate) ammonia at high pressure and high temperature. This ammonia from the generator reaches condenser at point 2 and the lean ammonia solution deposits into the separator (below) where from by gravity it goes back to absorber. The condenser absorbs the latent heat of the ammonia vapor. As a result the ammonia converts into liquid and falls into the liquid receiver at 3 and then enters the evaporator at point 4. Liquid ammonia in the evaporator boils in low temperature and transforms into vapor by the absorption of heat. This low pressure ammonia gas then enters the absorber and thus completes the cycle of refrigeration.

Comparison between Vapor compression and vapor Absorption Refrigeration

In vapor absorption system compressor is not used, a pump is used. Compressor work is considerably large in comparison to pump. Moreover, heat as low grade energy is used here instead of work as compressor input in case of vapor compressor system. So the total energy consumption is considerably less in case of vapor absorption system. So it is more efficient. Vapor absorption is more suitable for situations where waste heat is available. However, equipments of vapor absorption system are more expensive than vapor compression system. Moreover, due to easy availability of electrical power, vapor compression systems are much more widely used.

Problem-1. A vapor compression refrigeration system has to handle a cooling load of 2 ton. Find the power of the compressor in kW if the COP of the refrigeration system is given as 3.5.

Solution: $\mathbf{COP = Q_R/W_c}$ here, Q_R = Refrigerating capacity
W_c = Work input to the Compressor

Therefore, we get,

$3.5 = 2 \text{ ton} / W_c$

or, $W_c = (2 \text{ ton}) / 3.5 = (2 \text{ ton}) \times (3.5 \text{ kW}/1 \text{ ton})/3.5 =$ **2 kW Ans.**

Problem-2. A refrigeration system has got temperatures of 20^0C and -20^0C for the compressor and the evaporator sides, respectively. Find its COP. If compressor work is 3.5 kW, find the refrigeration capacity in ton.

Solution: $\mathbf{(COP)_{ref} = T_L / (T_H - T_L)}$

Here, T_H = Higher Cycle Temperature (Condenser / Compressor side Temperature), ^{o}K

T_L = Lower Cycle Temperature (Evaporator Temperature), ^{o}K

$\mathbf{(COP)_{ref} = (273 - 20) / (273+20-273+20) = 6.325}$

Again, $\mathbf{COP = Q_R/W_c}$ here, Q_R = Refrigerating capacity
W_c = Work input to the Compressor

Therefore, we get,

$6.325 = Q_R / (3.5 \text{ kW})$

or, $Q_R = 6.325 \times (3.5 \text{ kW}) = (6.325 \times 3.5 \text{ kW}) \times (1 \text{ ton} / 3.5 \text{ kW}) =$ **6.325 ton Ans.**

Problem-3. A refrigeration system has got temperatures of 10^0C and -10^0C for the compressor and the evaporator sides, respectively. Find its COP. If it has a cooling load of 7 ton, find the power required to drive the compressor.

Solution: $\mathbf{(COP)_{ref} = T_L / (T_H - T_L) = (273 - 10) / (273+10-273+10) = 13.15}$

Again $\mathbf{COP = Q_R/W_c}$

$13.15 = (7 \text{ ton}) / W_c$

or, $W_c = (7 \text{ ton}) / 13.15 = (7 \text{ ton}) \times (3.5 \text{ kW}/1 \text{ ton})/13.15 = 1.86 \text{ kW} \approx$ **2 kW Ans.**

Air / Gas Cycle Refrigeration System (Bell-Coleman refrigeration System)

Air is used as refrigerant. There is no condensation and evaporation in an air cycle. It works on the reverse Brayton cycle instead of the reverse Rankine cycle. The air cycle machine is very common on gas turbine-powered 'jet' aircraft.

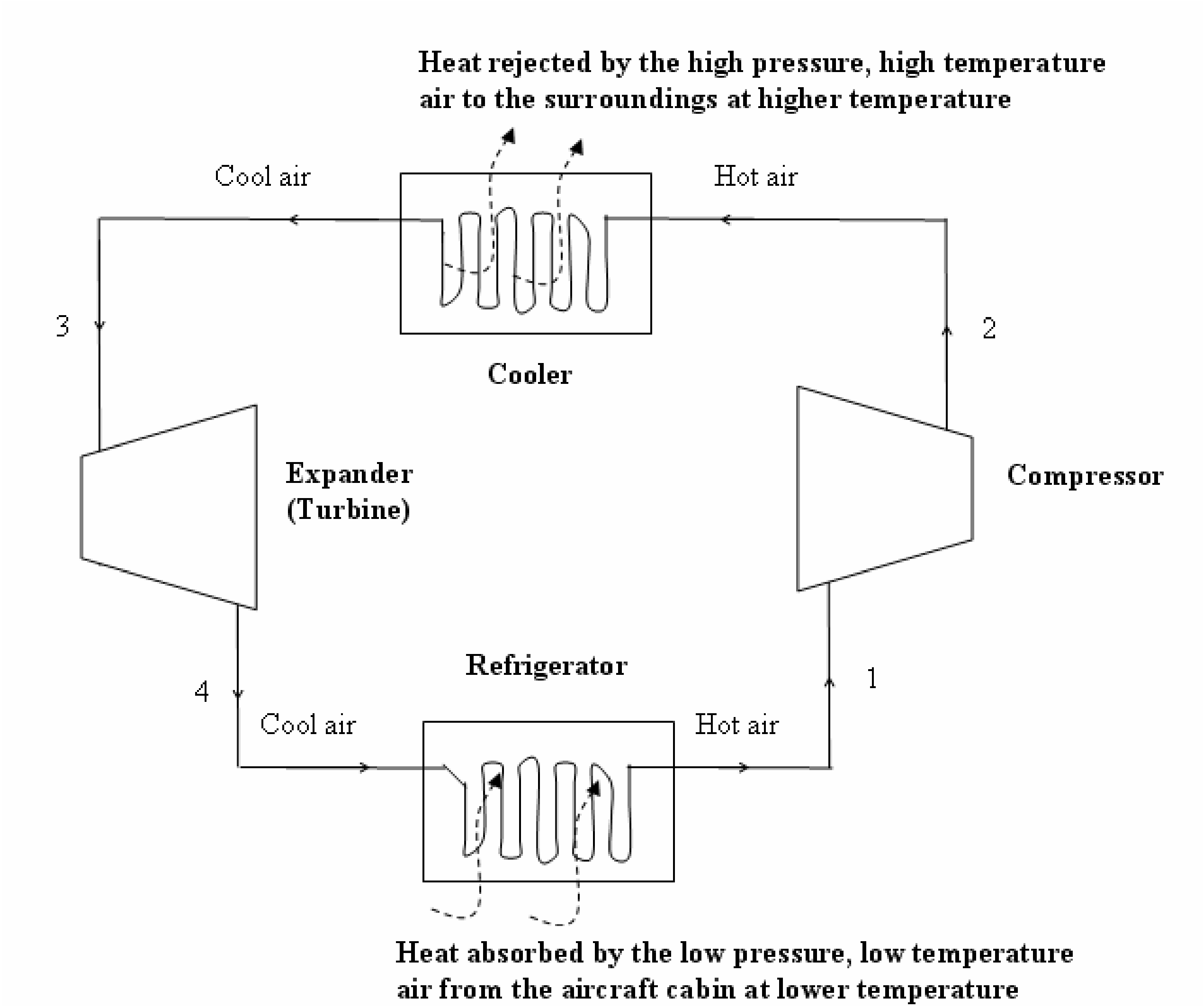


Fig-4a: Block/Schematic diagram of air /gas cycle refrigeration system

As shown in the 4a and 4b, the low pressure air from the refrigerator (cabin) is compressed in the compressor from 1 to 2, to increase both pressure and temperature. The air is then cooled to state 3 in the air cooler. Its pressure is also reduced to cabin pressure in the turbine to state 4, as a result its temperature drops. The cold air at state 4 is supplied to the cabin. It picks up heat as it flows through the cabin to its exit at state 1.

Even though the COP of air cycle refrigeration is very low compared to vapour compression refrigeration systems, it is still found to be most suitable for aircraft refrigeration systems as:

i. Air is cheap, safe, non-toxic and non-flammable. Leakage of air is not a problem

ii. The aircraft engine already consists of a high speed turbo-compressor, hence separate compressor for cooling system is not required. This reduces the weight per kW cooling considerably. Typically, less than 50% of an equivalent vapour compression system.

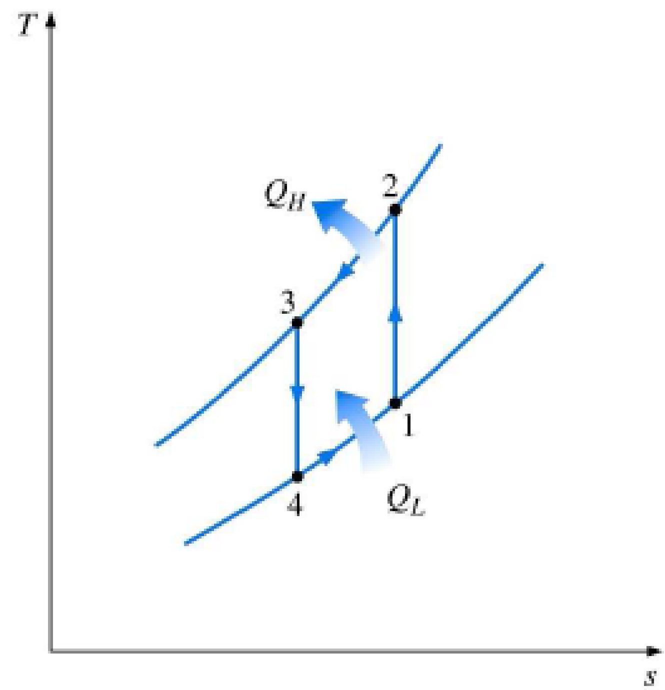


Fig-4b: Reversed Brayton cycle for air /gas cycle refrigeration system

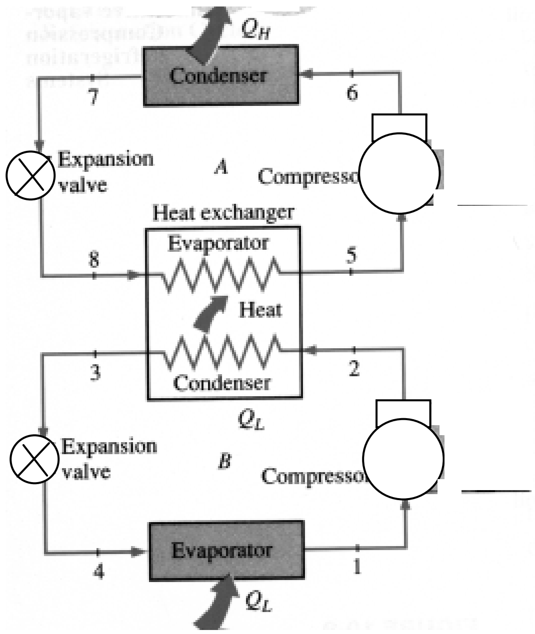
<u>Processes involved in the reversed Brayton cycle for air / gas cycle refrigeration system:</u>

1-2: isentropic compression,
2-3: constant pressure heat rejection at high temperature,
3-4: isentropic expansion
4-1: constant pressure heat addition at low temperature

<u>Thermoelectric refrigeration</u>

Thermoelectric cooling uses the Peltier effect to create a heat flux between the junction of two different types of materials. This effect is commonly used in camping and portable coolers and for cooling electronic components and small instruments.

Cascade Refrigeration Systems



- Cascade system consists of a series of vapor compression systems to achieve very low temperature not feasible by using a single system.

- Used in industrial applications where quite low temperatures are required

- Refrigeration cycle is performed in stages
- The refrigerant in the two stages doesn't mix
- Higher efficiency results but also a higher first cost

Magnetic refrigeration

In magnetic refrigeration, the refrigerant is often a paramagnetic salt. A strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. A heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and the magnetic field is switched off. This increases the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of the heat sink. Its applications have so far been limited to cryogenics and research.

Other methods of refrigeration

Vapor ejection refrigeration is used where waste steam is available. Warm water is sprayed in a flash chamber where vacuum is maintained by an ejector. As water flashes some portion of it becomes vapor taking latent heat from water thereby cooling it.

Vortex tube used for spot cooling, when compressed air is available;

Thermoacoustic refrigeration using sound waves in a pressurised gas to drive heat transfer and heat exchange.

Cryogenics refers to ultra low temperature refrigeration system using any of the above methods.

Air Conditioning (A/C)

An air conditioning system, or a standalone ***air conditioner***, provides cooling, heating, humidity control, filtering and ventilation (oxygen supply) for all or part of a house or building. On the other hand, an ***air cooler*** only cools the air (may do some filtering too).

Types of A/C System

1. Window type
2. Split Type
3. Chiller Type (Central A/C)

Window Type A/C System

Major Components: (i) A compressor, (ii) An expansion valve, (iii) A hot coil, i.e., condenser (on the outside), (iv) A chilled coil i.e., evaporator (on the inside), (v) Two fans and (vi) A control unit.
Refrigerant such as R-12 or R-22 are used to provide refrigeration effect. It actually is a vapor compression refrigeration system whose evaporator cools only the air.
Most residential window type air conditioning units range in capacity from about 1 to 2.5 tons of refrigeration.

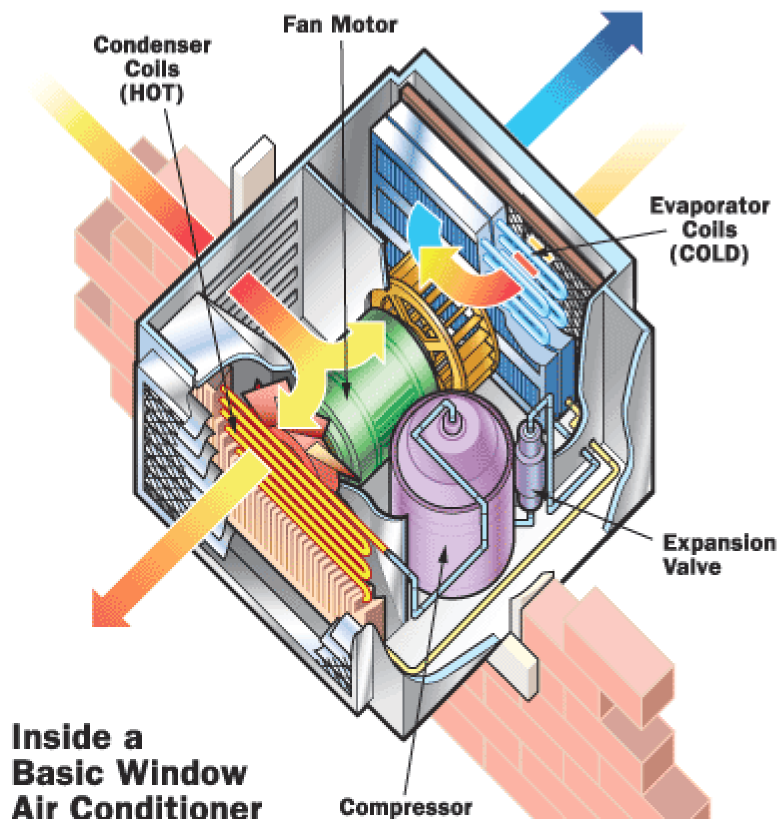


Fig-5a: Window-type A/C System

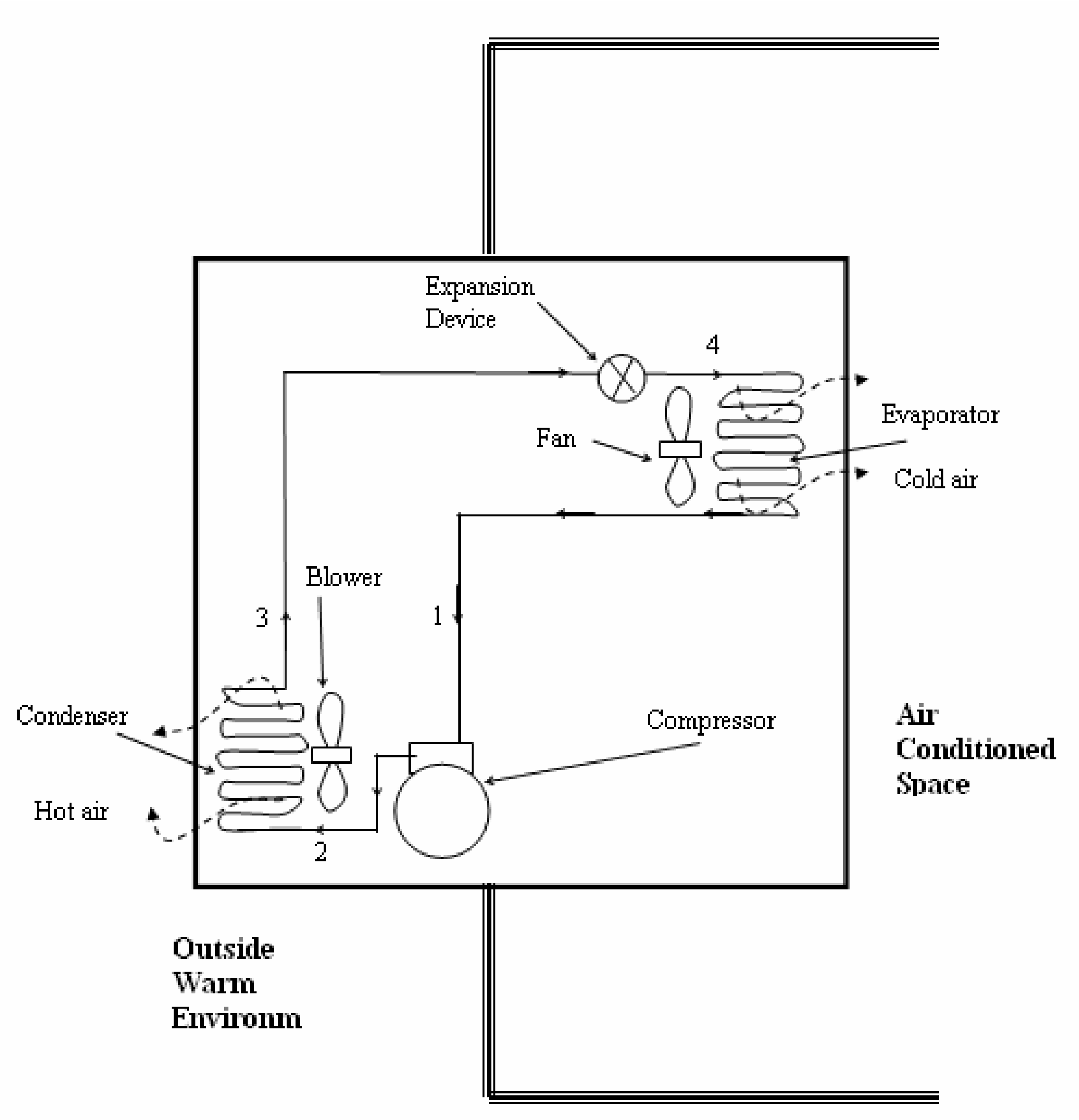


Fig-5: Block diagram of a Window-type A/C System

<u>Split-system AC Units</u>

<u>Major Components:</u>
A split-system air conditioner splits the hot side from the cold side of the system.
Cold side (Fan-coil unit) - Placed inside

(i) An expansion valve
(ii) A chilled coil placed in Air Handler Unit

Hot side (Condensing Unit)-Placed Outside/Rooftop

(iii) A weather-resistant compressor
(iv) A hot coil (on the outside)
(v) Two fans
(vi) Some control logic

Most residential split type air conditioning units range in capacity from about 1.5 to 7 tons of refrigeration.

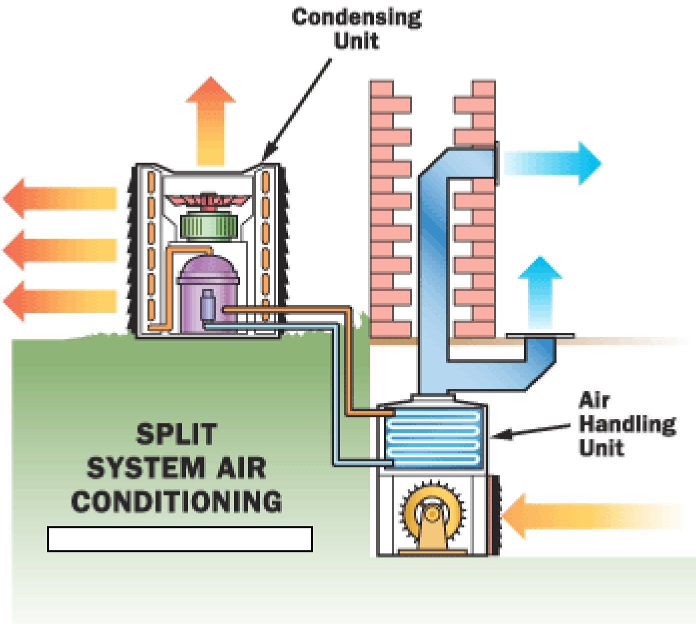


Fig-6a: Split-type A/C System

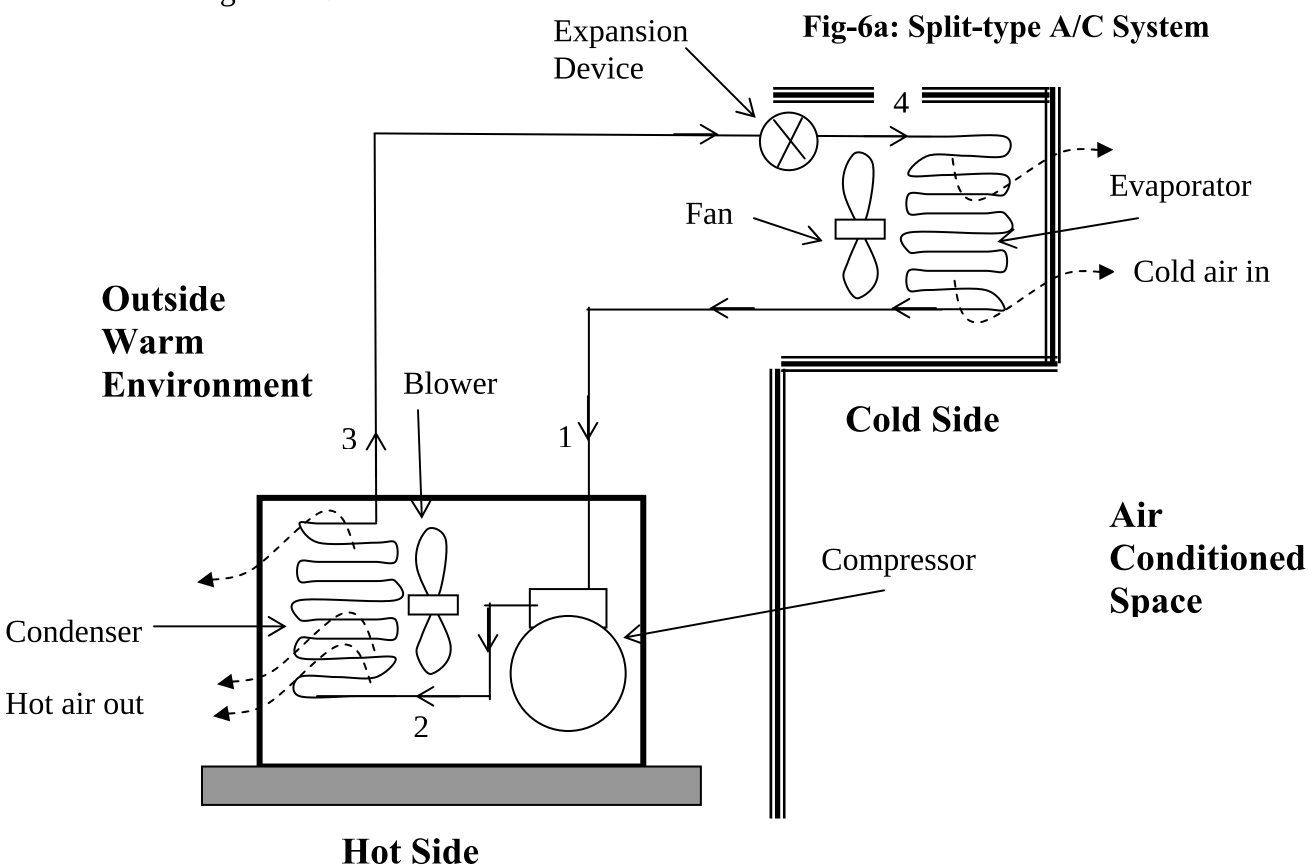


Fig-6b: Block diagram (Schematic) of a Split-type A/C System

Chilled-water and Cooling-tower A/C Units (Central A/C System)

Major Components: (i) Chiller (a complete vapor compression or absorption refrigeration system), (ii) Air Handling Unit (AHU), (iii) Cooling Tower.

In a chilled-water system, the entire air conditioner (chiller) lives on the roof or behind the building. The chiller cools water to between 4 to 7^{o} C. This chilled water is then piped throughout the building and connected to air handling units (AHUs) as needed. The AHU cools the air by using this chilled water and supply the cooled air through ducts to the conditioned space.
Central air conditioning units range in capacity from about 15 to 3500 tons of refrigeration.

Air conditioner Efficiency

EER (energy efficiency ratio) = BTU/watts (Bigger EERs are better)
[BTU= British Thermal Unit; 1 BTU = 1.055 kJ]
Old AC's EER= 6 – 8; New AC's EER= 10 – 13; EER=3.412*(COP)
Typical air conditioner: $8 < EER < 12$ for which is $2.3 < COP < 3.5$
Another Performance Parameter for A/C= **kW/ton; Usually 0.6 to 2.0**

Cooling Load:

Thumb rule, **1 ton per 200 or 300 ft^2 of standard floor space**.

Factors to be considered for calculating cooling load:

1. Sensible heat gains: solar heat, body heat of persons inside, heat electrical fittings and electronic appliances such electric bulb, ceiling fan motor, television, computer, heat from any other things inside the conditioned space.
2. Latent heat gains: heat from sweat of human beings, steam or vapor from things inside.
3. Heat gains from ventilating air: sensible heat gain due to temperature difference of inside and outside air and latent heat gain due to air-humidity difference between inside and outside air.

Air Circulation:

CFM required = Number of persons x Factor

CFM = Cubic feet per minute ventilating air
Factor = 7.5 (if there is no smoker) upto 40 (if there are smokers)

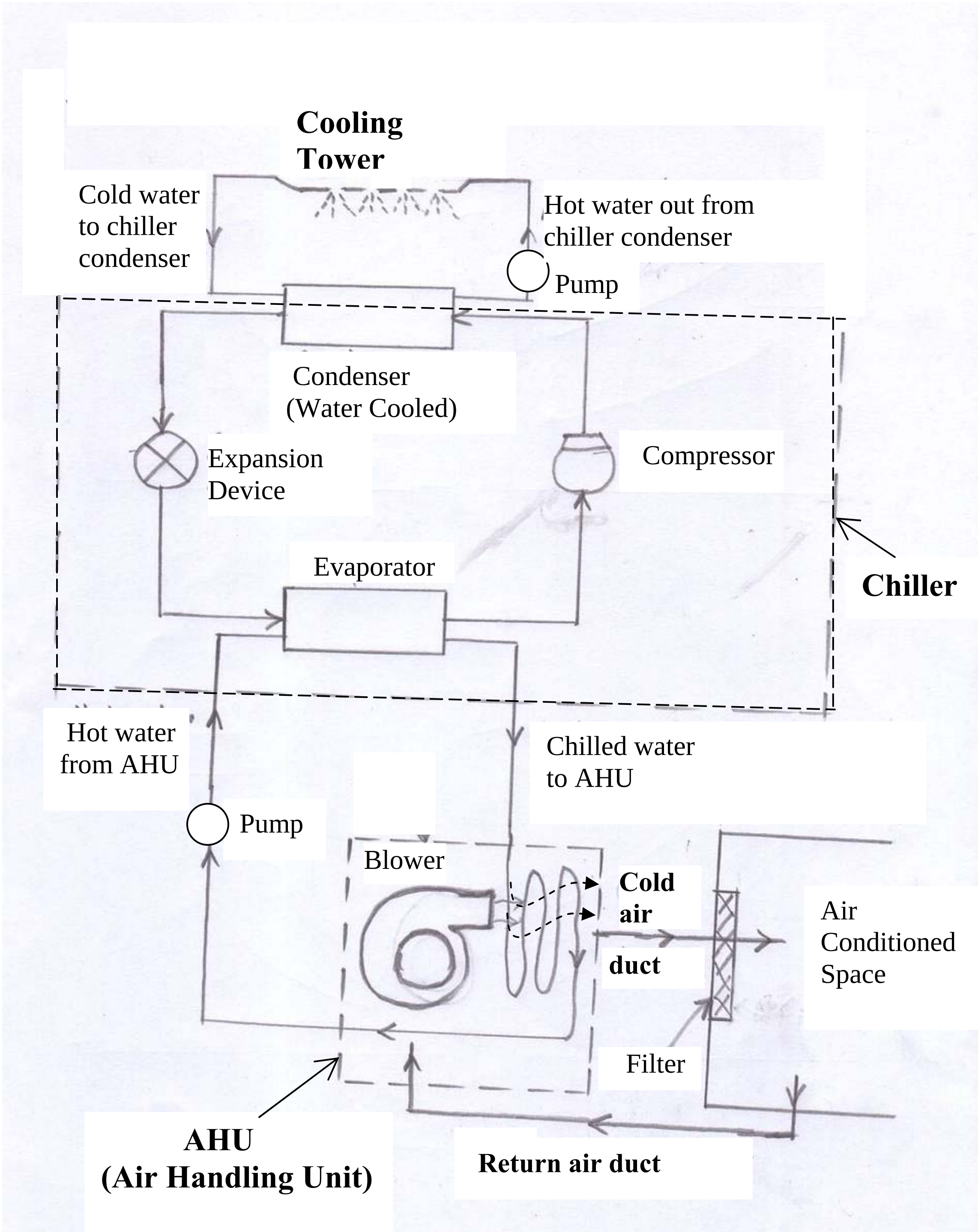


Fig-7: Chiller-type A/C System (Central A/C)

[The chiller is a refrigeration system (a vapor compression system). Its condenser is water-cooled. It usually employs a cooling tower to cool its condenser-cooling water.]

Psychrometry

Psychrometry is the study of air and its moisture content.

Psychrometric Parameters

1. Dry bulb temperature (t_{db})
2. Wet bulb temperature (t_{wb})
3. Absolute humidity (g)
4. Relative humidity (RH)
5. Dew point (t_{dew})

Dry bulb temperature

The temperature that is shown by a normal mercury in glass-tube thermometer is the dry bulb thermometer.

Wet bulb temperature

The temperature that is shown by a mercury in glass-tube thermometer when its probe is wrapped with a wet cloth (wick) is the wet bulb thermometer.

Dry bulb and wet bulb temperatures can be obtained simultaneously by using a sling psychrometer (hygrometer).

Sling Psychrometer (Hygrometer)

Absolute Humidity

Absolute humidity indicates the moisture content in the air.

Absolute Humidity

The ratio of the actual quantity of moisture contained in a given parcel of air to the maximum quantity of moisture the air can contain at a certain temperature is called the relative humidity, RH.

RH = (m/M) x 100%

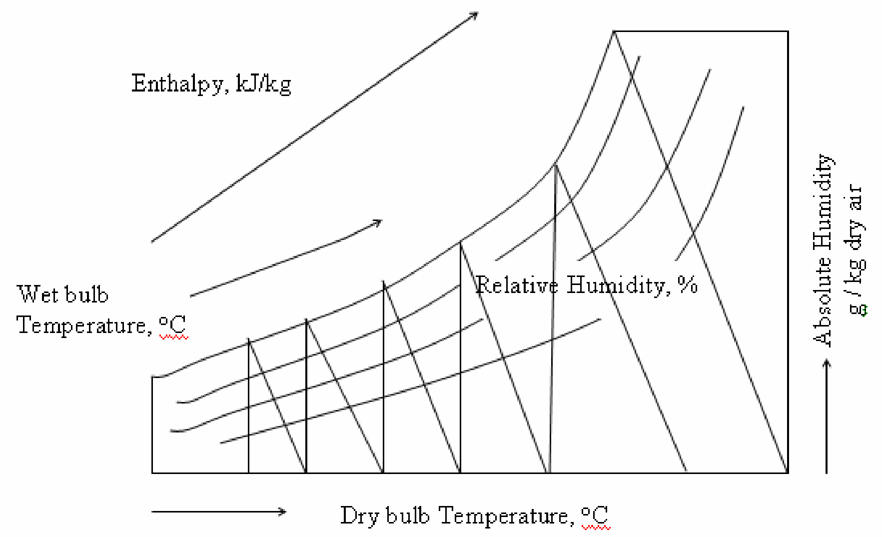
Where, m = quantity of actual moisture at a certain temperature (g/kg of dry air)
M = maximum quantity of moisture the given air parcel can contain at the same temperature.

When the relative humidity of air is 100%, both the dry bulb and wet bulb temperatures are same.

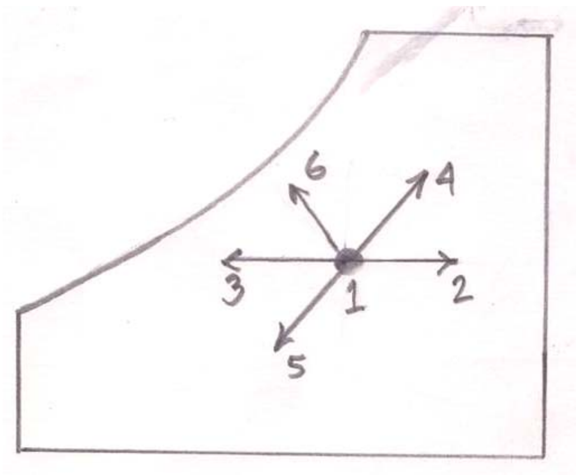
Dew Point

This is the temperature to which a given air parcel has to be cooled to make it 100% saturated with its actual moisture content.

Typical Layout of a Psychrometric Chart with Constant Property Lines

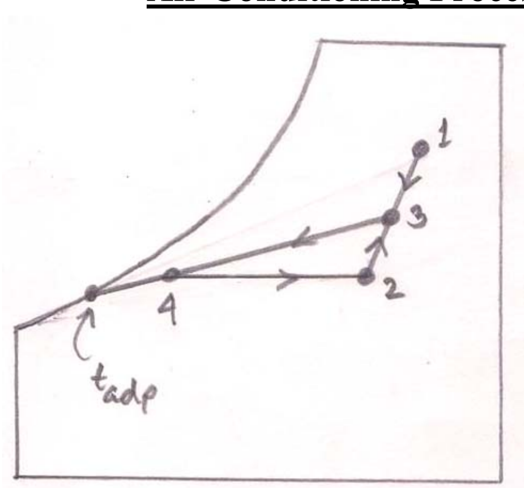


Some Important Psychrometric Processes



1-2: Sensible heating
1-3: Sensible cooling
1-4: Heating with humidification (used in winter air conditioning)
1-5: Cooling with dehumidification (used in summer air conditioning)
1-6: Cooling with humidification (Evaporative cooling, used in cooling tower for industrial cooling)

Air Conditioning Process in a Psychrometric Chart



Points on the chart:
1 – condition of atmospheric air
2 – designed air in the conditioned room
3 – condition of air (1+2), when mixes together by the suction by AHU in front of the cooling coil.

The above air gets cooled by coming in contact with cooling coil and represented by point 4. Points 3 and 4 if joined and extended, the line meets the 100% saturation line at point t_{adp} which is called apparatus dew point. This t_{adp} is used in selecting the equipments for A/C system.

Problem-4. A Split type A/C unit working on vapor compression refrigeration system has got hot-side temperature (compressor-side) of 37^0C and the cold-side temperature (evaporator side) of 12^0C. Find its COP. If it has a cooling load of 5 ton, find the power rating of its compressor.

Solution: $\mathbf{(COP)_{ref} = T_L / (T_H – T_L) = (273+12) / (273+37–273–12) = 11.4}$

Again $\mathbf{COP = Q_R/W_c}$

$11.4 = (5\ \text{ton}) / W_c$

or, $W_c = (5\ \text{ton}) / 11.4 = (5\ \text{ton}) \times (3.5\ \text{kW}/1\ \text{ton})/11.4 =$ **1.5 kW Ans.**

Problem-5. In a hall room there are in all 16 persons, 10 of them are sitting on chairs and reading books. 6 persons are standing and doing light works. There are 5 tube-lights and 4 ceiling fans. Calculate the cooling load due to occupants and electric appliances.

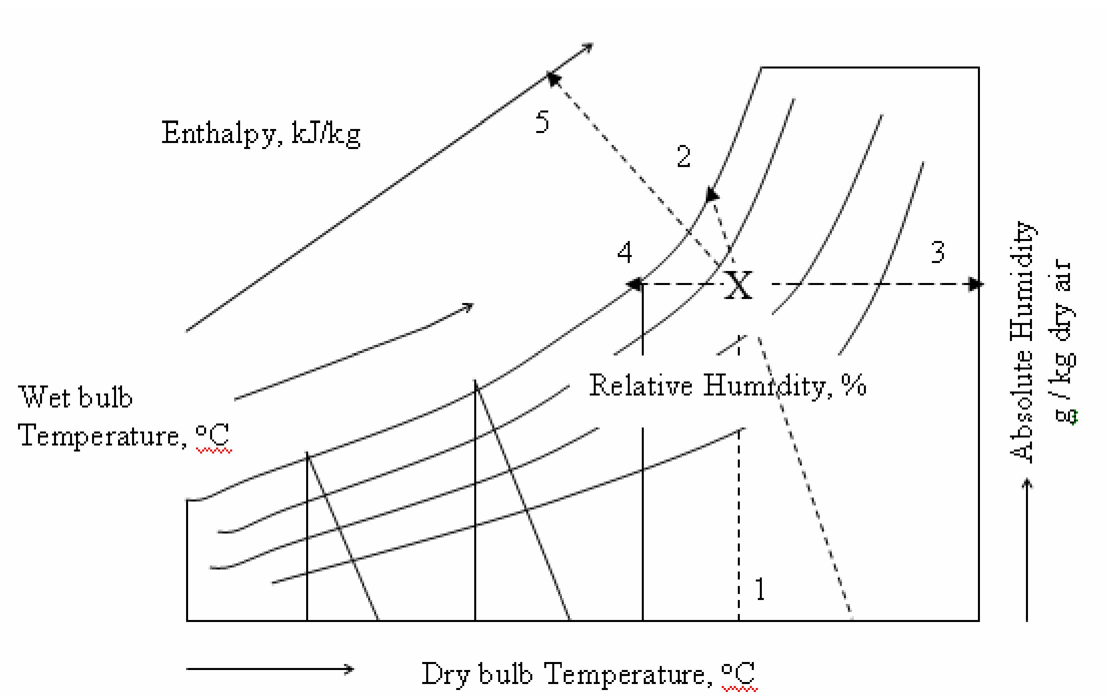
Solution: Sensible heat and latent heat for resting person are 180 Btu/hr and 150 Btu/hr respectively, for light work (standing) Sensible heat and latent heat are 200 Btu/hr and 250 Btu/hr respectively, Heat gain due to tube lights are @170 Btu/hr and heat gain due to ceiling fan are @220 Btu/hr.

Total cooling load = Sitting persons, 10*(180+150) + standing person, 6*(200+250) + tube lights, 5*170 + ceiling fans, 4*220 = **7730 Btu/hr. Ans.**

Problem-6. Moist air has a dry-bulb temperature of 30°C, and a wet-bulb temperature of 26°C. Using a Psychrometric Chart, find the following:

1. The Relative Humidity (RH), %
2. The Absolute Humidity
3. The dew-point temperature
4. The enthalpy
5. The specific volume

Solution: For t_{db} = 30°C and t_{wb} = 26°C, following the steps shown in the picture below using the given psychrometric chart, We get from cutting point X of 1 (t_{db}) and 2 (t_{wb}) as shown,



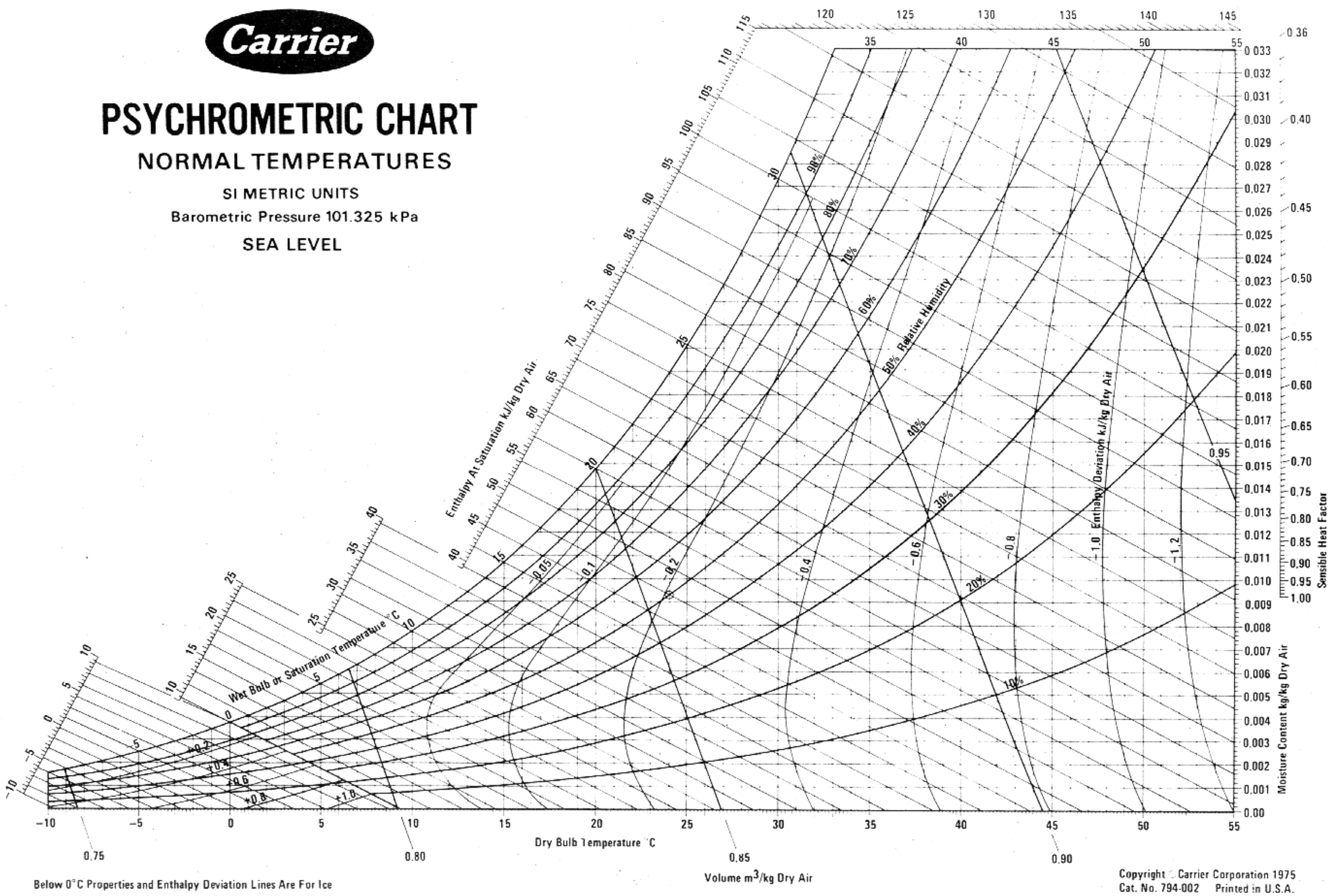
1. Relative Humidity, RH = 72%. (steps 1 &2)

2. Absolute Humidity, w = 198 g / kg of dry air (step 3)

3. Dew-point temperature, t_{dew} = 24.7 ^{o}C (step 4)

4. Enthalpy, h = 80 kJ/kg (step 5)

5. Specific volume, v = 0.88 m^3 / kg



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