MEBS6006 Environmental Services I

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Refrigeration Systems

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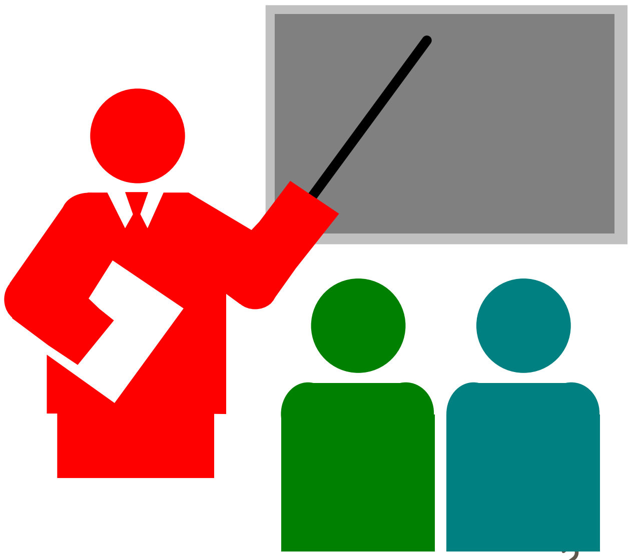
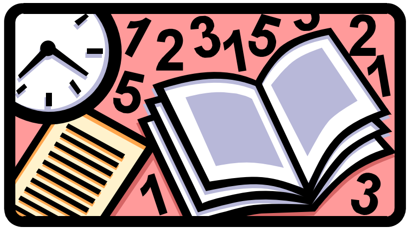


Refrigerants



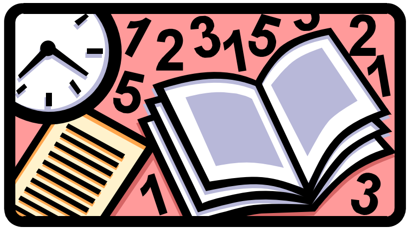
Definitions of Refrigerants

- A refrigerant is a fluid used for heat transfer in a refrigeration system.

- Most refrigerants
  - absorb heat during vaporisation (from liquid state to gaseous state) at low temperature and low pressure, and
  - reject heat during condensation (from gaseous state to liquid state) at a higher temperature and higher pressure.

- Some refrigerants produce a refrigeration effect when they throttle and expand in the refrigeration cycle.

Refrigerants

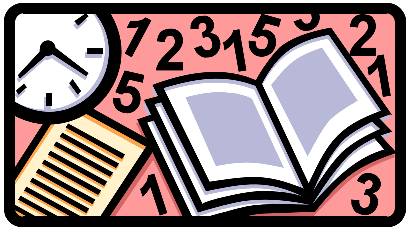


Classification of Refrigerants

Refrigerants most commonly used refrigeration systems can be classified into four groups:

- hydrocarbons,
- inorganic compounds,
- halocarbons, and
- azeotropes

Refrigerants



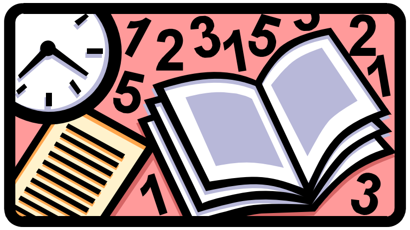
Hydrocarbons

- Examples: ethane, propane, butane and isobutane.
- Source: Produced from petroleum in an oil refinery.
- Used in the refrigeration systems in oil refineries and the petrochemical industry due to their low cost and ready availability.
- Flammable and so safety precautions are of utmost importance in the petrochemical industry.

Inorganic compounds

- Inorganic compounds : e.g. ammonia NH_3, Lithium Bromide LiBr

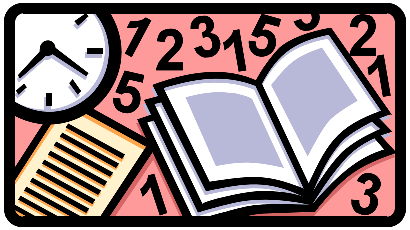
Refrigerants



Halocarbons

- Refrigerants belonging to the halocarbon group are derivatives of the hydrocarbons obtained by substituting chlorine or fluorine for the hydrogen atoms in methane and ethane.
- As chlorine and fluorine are both halogens, this group of refrigerants is called the halogenated hydrocarbons or halocarbons.
- They are sometimes referred to *Freon* which are colourless, non-inflammable, non-corrosive to most metals and generally non-toxic
- Common refrigerants in this group are R-11, R-12, R-13 and R-22.

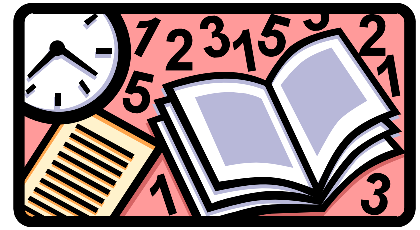
Refrigerants



Azeotropes

- An azeotrope is a mixture of two substances which cannot be separated into its components by distillation.
- It evaporates and condenses as a single substance and Its properties are completely different from its constituents.
- For example, azeotrope R-500 is a mixture composed of 73.8 per cent R-12 and 26.2 per cent R-152.

Refrigerants



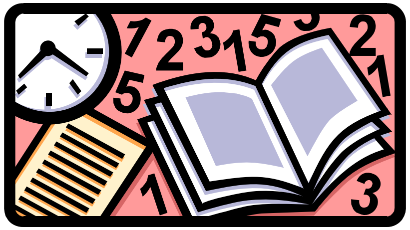
Selection of a suitable refrigerant

Evaporating temperature required during operation, the coefficient of performance (COP), safety requirements, and the size and location of the refrigeration plant, etc.

In order to select a suitable refrigerant for a refrigeration system of known size and evaporating temperature, the following factors must be considered:

- Mass / volume flow rate required per kW of refrigeration capacity
- Coefficient of performance in the refrigeration cycle
- Safety requirements
- Physical properties
- Operating properties
- Cost.

Refrigerants



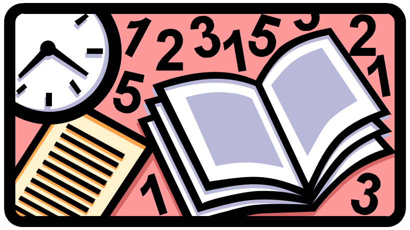
From CFC to HCFC to HFC

CFCs (chlorofluorocarbons)
High ozone-depleting potential (ODP) contributing to the breakdown of the ozone layer, are banned by the Montreal Pro (an international agreement to protect the earth's ozone layer) and ceased to be manufactured in the European Community (e.g. R11, R12 and R114.)

HCFCs (hydrochlorofluorocarbons)
These have limited ODP are **classified under** the Montreal Protocol as *transitional substances* and are due to be phased out early in next century. Examples are R22, R123 and R124.

HFCs (hydrofluorocarbons)
These contain no chlorine and therefore have zero ODP and not controlled by the Montreal Protocol. Examples are R125, R134a and R152a. R134a can be substituted directly, requiring replacement of some serviceable' components only for R12.

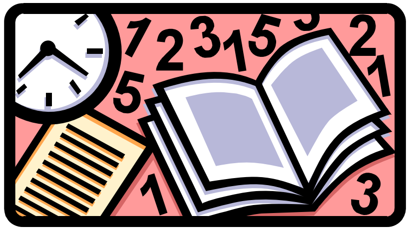
Refrigerants



Global Warming Potential (GWP)
In addition to an ODP classification, refrigerants are also given ratings for global warming potential (GWP), an index providing a simple comparison with carbon dioxide which has an index rating of unity.

Prevention of Leakage
Consideration should be given to limiting the volume of refrigerant gas in a system together with improved standards of design and installation for refrigerant pipework in order to reduce the risk of leakage.

Refrigerants

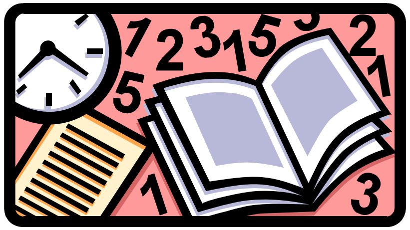


Hong Kong Present Situation on CFC

In line with an international agreement to protect the earth's ozone layer (Montreal Protocol), the enactment in 1989 of the Ozone Layer Protection Ordinance and its subsequent enforcement has brought about a total ban on import of CFCs has been taken into effect on ***1 January 1996.***

No matter how carefully the air-conditioning equipment is maintained, some refrigerants are lost through small leaks in pipes and valves, during equipment overhauls or accidents. There has been no CFCs available to replenish these losses (in principle).

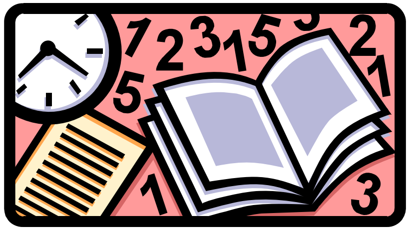
Refrigerants



Eliminate dependence on CFC for AC plant for existing installations

- Routine leak checks at regular intervals
- Installation of a refrigerant leak detection system to minimize the leakage
- Recover and recycle the refrigerant during servicing and maintenance of the refrigerant circuits (a mandatory requirement under LAW to recover the refrigerant from large plant using CFC such as R-12)
- Paying particular attention to joints, seals, and gaskets.
- After completion of any servicing or repair work, thoroughly check for leaks before recharging with refrigerant.
- Replace refrigerants in existing systems by HCFCs (retrofit works allowing the run of HCFCs or azeotrope. Minor modifications to equipment needed and allow for a slight reduction in machine efficiency after conversion.
- Install new chillers running on non-CFC refrigerants

Refrigerants



Ideal refrigerants

- Having the desired thermodynamic properties
- Nontoxic
- Non-flammable
- Completely stable inside a system
- Environmentally friendly - even after decomposition of products-and abundantly available or easy to manufacture
- Self-lubricating
- Compatible with other materials used to fabricate and service refrigeration systems
- Easy to handle and detect
- System not operating at extreme pressures, either high or low

Properties of refrigerants

Properties	*Refrigerant*						
	Ammonia	*R11*	*R12*	*R22*	*R123*	*R134a*	*R407C*
Gauge pressure (kPa)							
condenser (30 °C)	+1060	+24.8	+642	+1100	+8.2	+670	1160
evaporator (−15 °C)	+155	−80.6	+81.2	+195	−85.4	+62.6	189
evaporator (−5 °C)	+404	−52.5	+254	+427	−60.5	+249	321
Boiling point (°C) (standard pressure)	−33.3	+23.8	−29.8	−40.8	+27.8	−26.1	−43.8
Critical temperature (°C)	1333	198	111	96	184	101	87.3
Volume of vapour at −15 °C (m^3/kg)	0.509	0.766	0.093	0.078	0.873	0.121	0.09
Latent heat of evaporation at −15 °C (kJ/kg)	1320	198	162	218	175	187	212
Theoretical energy input per unit ÷ energy output (kW/kW)	0.211	0.200	0.213	0.216	0.203	0.217	–
Coefficient of performance (27 °C to − 15 °C)	4.75	5.00	4.69	4.65	4.93	4.61	–
Ozone depleting potential (ODP)	0	1.0	1.0	0.05	0.014	0	0
Global warming potential (GWP)	0	1500	4500	510	29	1600	1980

Basic Refrigeration Cycle

Refrigeration Cycle: PH diagram

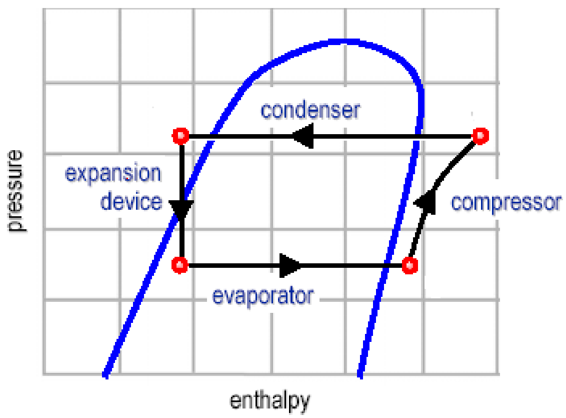
Evaporator

- A diagram of a typical vapor-compression refrigeration cycle is superimposed on a pressure-enthalpy (P-*h*) chart to demonstrate the function of each component in the system.

- The **pressure-enthalpy chart** plots the properties of a refrigerant—refrigerant pressure (vertical axis) versus enthalpy (horizontal axis).

- The cycle starts with a cool, low-pressure mixture of liquid and vapor refrigerant entering the evaporator where it absorbs heat from the relatively warm air/water or other fluid that is being cooled.

- This transfer of heat boils the liquid refrigerant in the evaporator, and this superheated refrigerant vapor is drawn to the compressor.

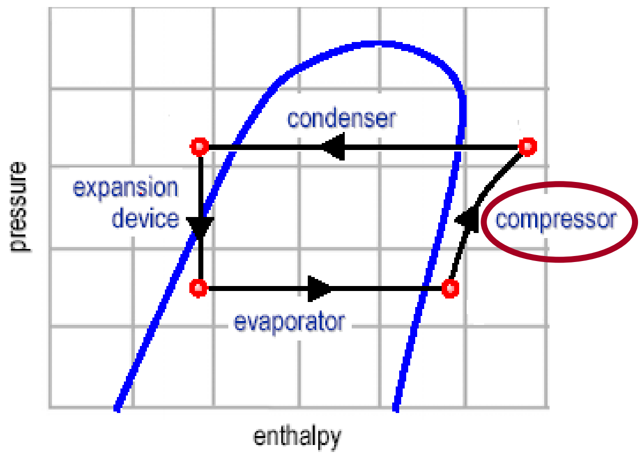


Basic Refrigeration Cycle

Refrigeration Cycle: PH diagram

Compressor

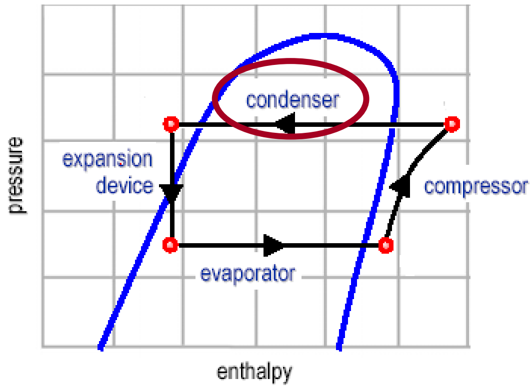
- The compressor draws in the superheated refrigerant vapor and compresses it to a pressure and temperature high enough that it can reject heat to another fluid.
- This hot, high-pressure refrigerant vapor then travels to the condenser.



Basic Refrigeration Cycle

Refrigeration Cycle: PH diagram

Condenser

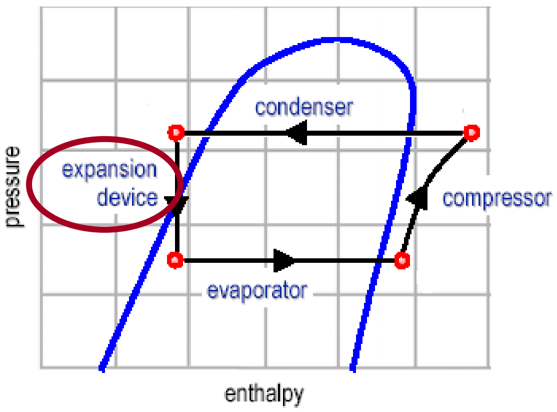


- Within the condenser, heat is transferred from the hot refrigerant vapor to relatively cool ambient air or cooling water.
- This reduction in the heat content of the refrigerant vapor causes it to desuperheat, condense into liquid, and further subcool before leaving the condenser for the expansion device.

Basic Refrigeration Cycle

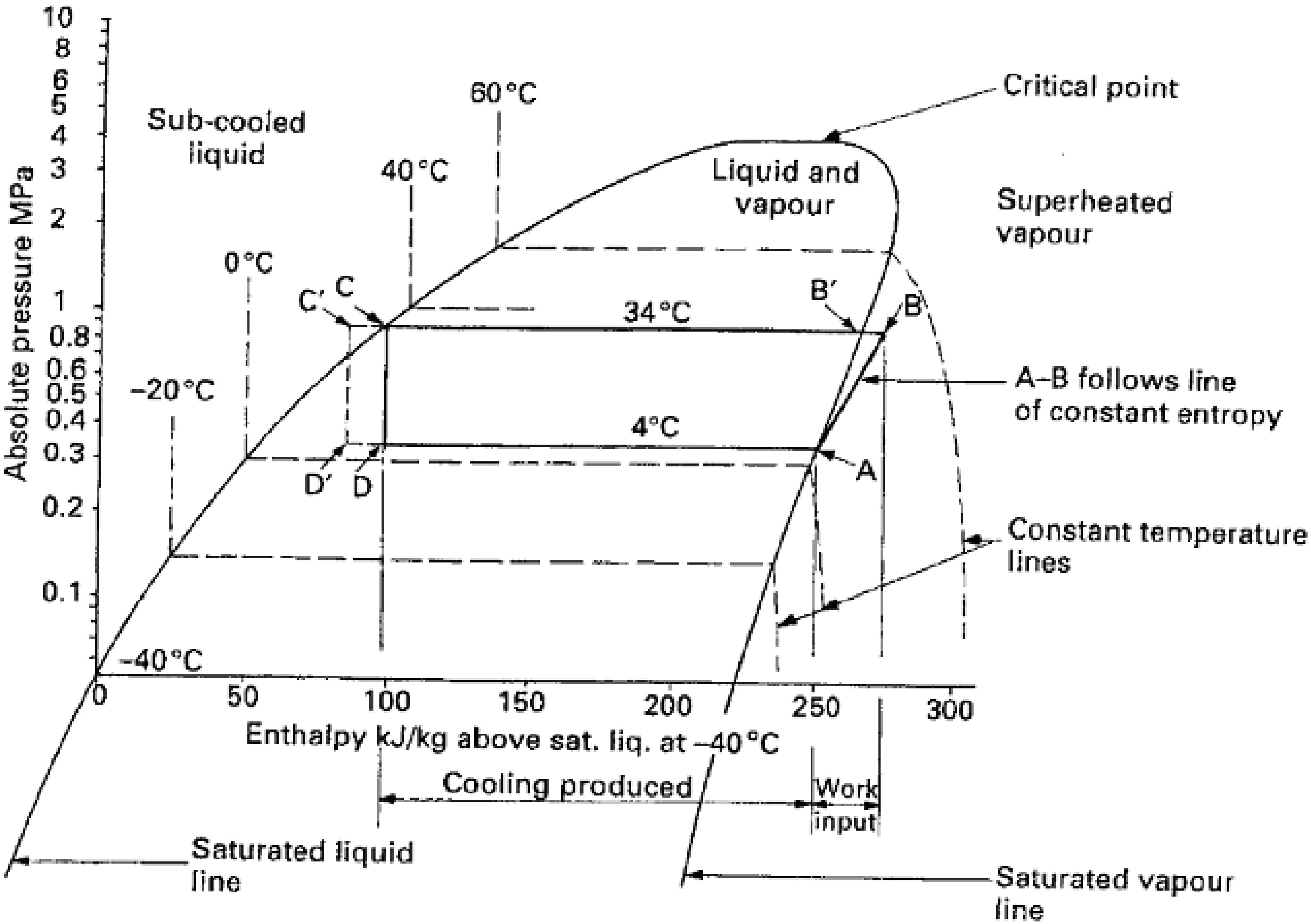
Refrigeration Cycle: PH diagram

Expansion Device



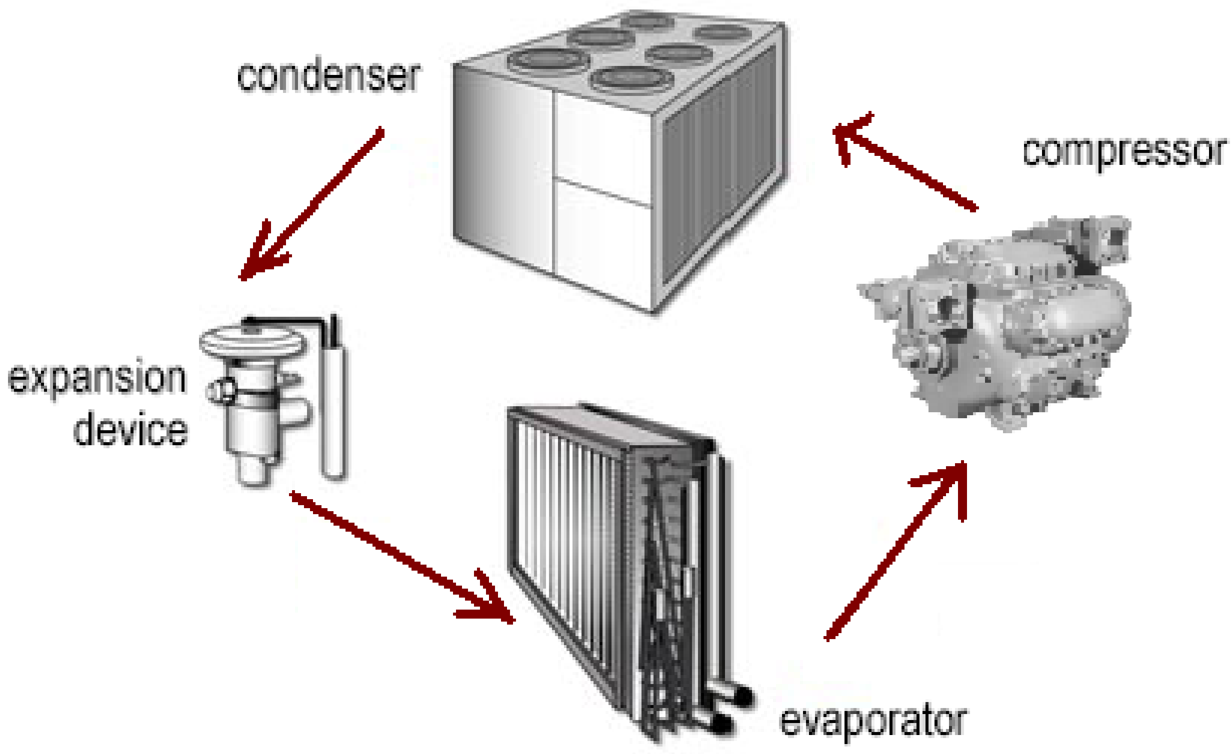
- The high-pressure liquid refrigerant flows through the expansion device, causing a large pressure drop that reduces the pressure of the refrigerant to that of the evaporator.
- This pressure reduction causes a small portion of the liquid to boil off, or flash, cooling the remaining refrigerant to the desired evaporator temperature.
- The cooled mixture of liquid and vapor refrigerant then enters the evaporator to repeat the cycle.

Basic Refrigeration Cycle



Pressure–enthalpy (total heat) diagram for Refrigerant 134a

Major Components in Vapor Compression Cycle



Major Components of Vapour Compression System

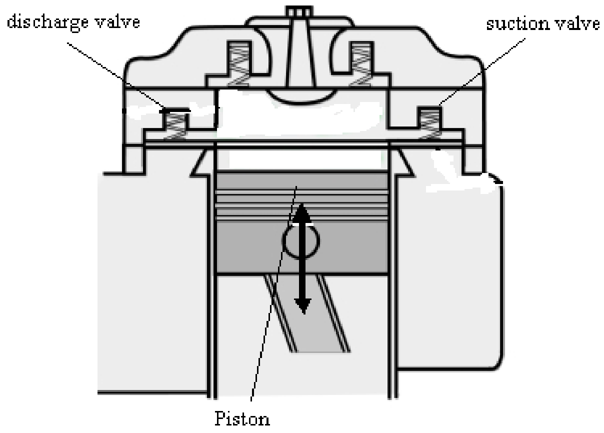
Compressor

There are primarily four types of compressors used in the air-conditioning industry:

- Reciprocating,
- Scroll,
- Screw
- Centrifugal.

Major Components of Vapour Compression System

Reciprocating Compressor



The refrigerant vapor is compressed by a piston that is located inside a cylinder.

The piston is connected to the crankshaft by a rod.

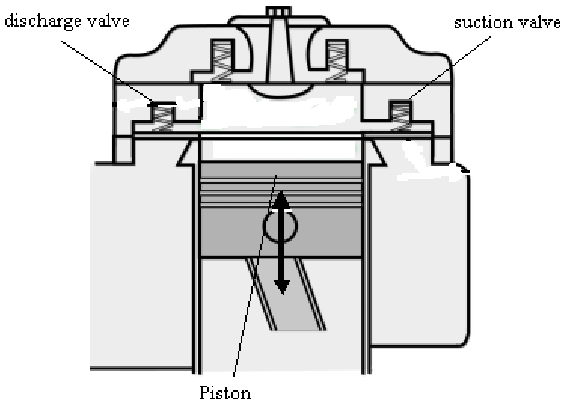
As the crankshaft rotates, it causes the piston to travel back and forth inside the cylinder.

Suction valve and the discharge valve, are used to trap the refrigerant vapor within the cylinder during this process.

Major Components of Vapour Compression System

Reciprocating Compressor

Intake stroke



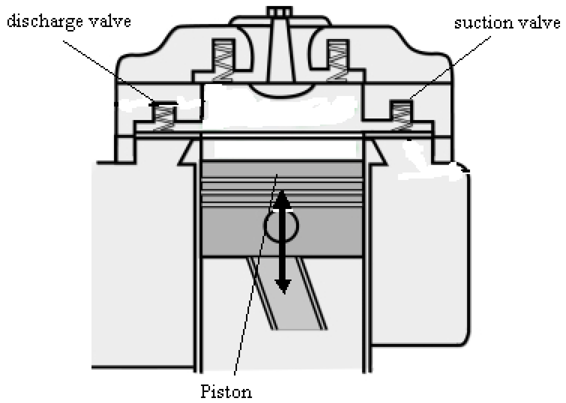
The piston travels away from the discharge valve and creates a vacuum effect

Reduction in the pressure within the cylinder to below suction pressure forces the suction valve to open and the refrigerant vapor is drawn into the cylinder.

Major Components of Vapour Compression System

Reciprocating Compressor

Compression stroke & discharge



The piston reverses its direction and travels toward the discharge valve, compressing the refrigerant vapor

The suction valve is then closed, trapping the refrigerant vapor inside the cylinder.

As the piston continues to travel toward the discharge valve, the refrigerant vapor is compressed.

The discharge valve is forced open and the compressed refrigerant vapor leaves the cylinder.

Major Components of Vapour Compression System

Reciprocating compressors

Cylinder unloading: suction valve on one or more cylinders to be maintained in a raised position by hydraulic pressure, so allowing the refrigerant gas to pass back and forth without check and thereby reducing the mass flow through the compressor.

A minimum gas flow must be maintained to minimise overheating and ensure adequate oil return.

Speed: the output of a reciprocating compressor is directly proportional to the speed of shaft rotation, which may be changed by varying the speed of the prime mover.

A certain minimum speed must be maintained for lubrication to be effective.

Major Components of Vapour Compression System

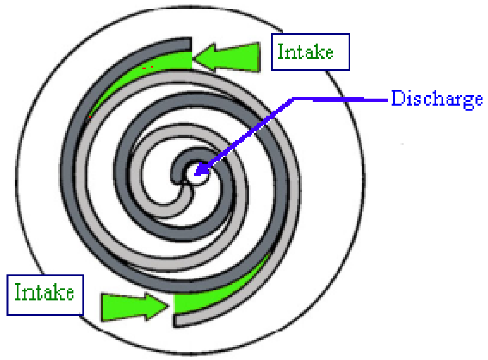
Scroll compressor

It works on the principle of trapping the refrigerant vapor and compressing it by gradually shrinking the volume of the refrigerant.

The scroll compressor uses two scroll to perform this compression process.

The stationary scroll contains a discharge port.

The the driven scroll is connected to a motor by a shaft and bearing assembly.

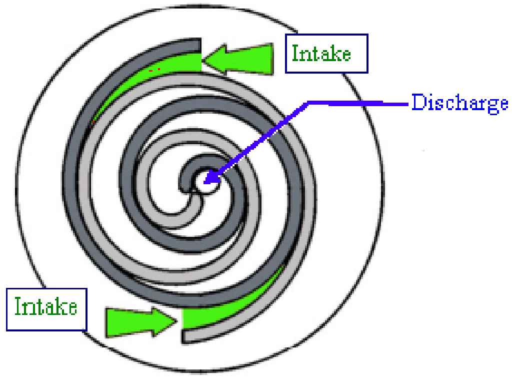


Scroll Compressor

Major Components of Vapour Compression System

Scroll compressor

The refrigerant vapor enters through the outer edge of the scroll assembly and discharges through the port at the center of the stationary scroll.



Scroll Compressor

The orbiting motion causes the relative movement between the orbiting scroll and the stationary scroll so that the pockets of refrigerant moving towards the discharge port at the center of the assembly.

Hence, there is a gradually decreasing in refrigerant volume and increasing in pressure.

Scroll compressors are widely used in heat pumps, rooftop units, split systems, etc.

Major Components of Vapour Compression System

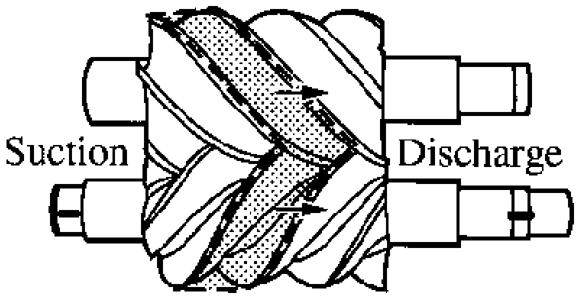
Scroll compressors

- Capacity control can be obtained using two-speed motors or multiple compressors.
- Although variable motor speed has been used it is not ideally suited for scroll compressors because it is not compatible with the method of radial compliance usually employed in scroll compressors which prevents damage by small quantities of liquid refrigerant or solid particles passing through the compressor.
- Speed control also creates difficulties with the compressor lubrication system.

Major Components of Vapour Compression System

Screw Compressor

Screw compressor traps the refrigerant vapor and compresses it by gradually shrinking the volume of the refrigerant.



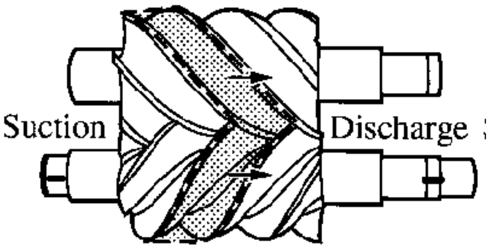
This particular screw compressor design uses two mating screw-like rotors (male and female rotors) to perform the compression process.

Only the male rotor is driven by the compressor motor. The lobes of the male rotor engage and drive the female rotor, so that the two parts counter-rotate.

Screw Compressor

Refrigerant vapor enters the compressor housing through the intake port and fills the pockets formed by the lobes of the rotors.

As the rotors turn, they push these pockets of refrigerant toward the discharge end of the compressor.



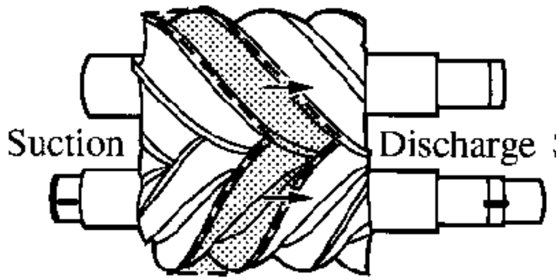
Major Components of Vapour Compression System

Screw Compressor

Continued rotation of the rotor lobes drives the trapped refrigerant vapor toward the discharge end of the compressor.

This action progressively reduces the volume of the pockets (compressing the refrigerant).

When the pockets of refrigerant reach the discharge port, the compressed vapor is released and the rotors force the remaining refrigerant from the pockets.



Major Components of Vapour Compression System

Screw compressors

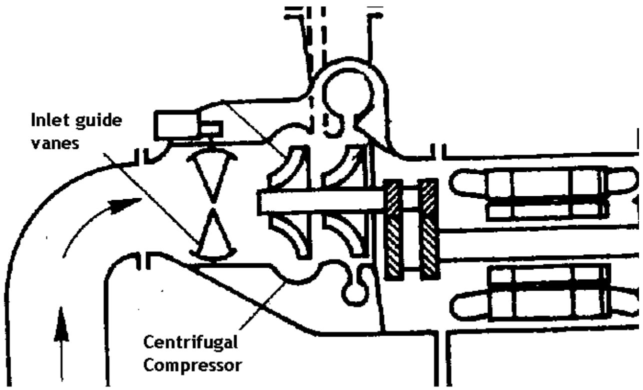
Sliding valve: Capacity control is normally obtained by varying the compressor displacement using a sliding valve to retard the point at which compression begins and, at the same time, reducing the size of the discharge port to obtain the desired volume ratio.

This typically allows 10% to 100% capacity control although below 60% of full load the compressor efficiency is very low.

Variable motor speed control using an inverter is also increasingly used and at low loads offers higher efficiency than the slide valve method.

Major Components of Vapour Compression System

Centrifugal Compressor



The **centrifugal compressor** adopts the principle of dynamic compression by converting kinetic energy to static energy to increase the pressure and temperature of the refrigerant.

A centrifugal compressor comprises rotating impeller the centre of which is fitted with blades that draw refrigerant vapor into radial passages that are internal to the impeller body.

Major Components of Vapour Compression System

Centrifugal Compressor

Since the impeller is constrained to rotate in one direction, work could only be transferred from impeller to the vapour tangentially.

The components of velocity in this direction are the whirl velocities.

Momentum = mass x velocity = mu_w
Force = rate of change of momentum = $mu_{w1} - mu_{w2}$
Assume with no pre-whirl, u_{w1} is zero.
Force = mu_{w2}

Power = Force x distance moved per second = $- mu_{w2}u_{b2}$

Where $u_{b2} = \pi$ Do N

with Do is impeller tip diameter and N is rotational speed

Major Components of Vapour Compression System

Centrifugal Compressor

Compressor would not have a negative input, therefore the

Power = $mu_{w2}u_{b2}$

Consider the slip factor $\sigma = \frac{u_{w2}}{u_{b2}}$

Power input = $m\sigma u_{b2}^2$ ------------ (1)

Power input = $m(h_2 - h_1)$ ------(2)

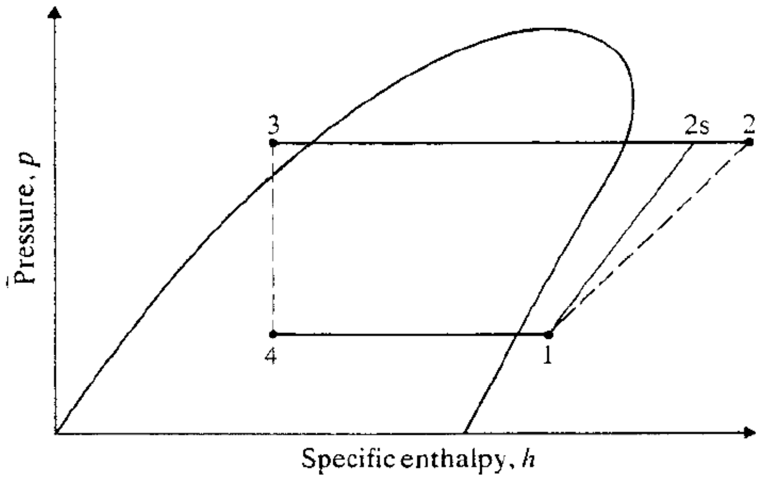
As (1) = (2)

Therefore

Rearranging,

$$u_{b2} = \sqrt{\frac{(h_2 - h_1)}{\sigma}}$$

Major Components of Vapour Compression System



$$\eta_s = \frac{\text{Isentropic work}}{\text{Actual work}} = \frac{\dot{m}(h_{2s} - h_1)}{\dot{m}(h_2 - h_1)} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Rate of heat *supply* to evaporator $\dot{Q}_E = \dot{m}(h_1 - h_4)$

Rate of heat *rejection* from condenser $\dot{Q}_C = \dot{m}(h_2 - h_3)$

Rate of work *input* to the compressor $\dot{W} = \dot{m}(h_2 - h_1)$

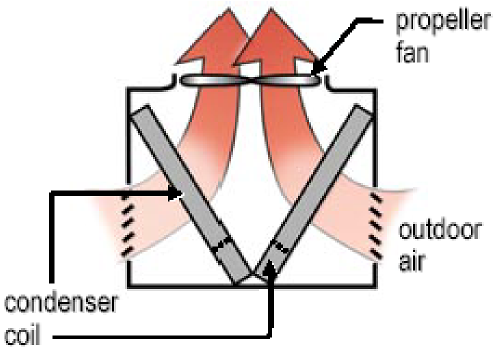
Major Components of Vapour Compression System

Air-Cooled Condensers

A typical air-cooled condenser uses propeller-type fans to draw outdoor air over a finned-tube heat transfer surface.

The resulting reduction in the heat content of the refrigerant vapor causes it to condense into liquid.

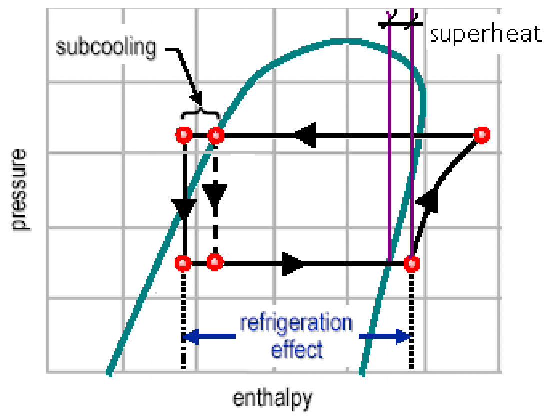
Within the final few lengths of condenser tubing (subcooler), the liquid refrigerant is further cooled below the temperature at which it was condensed.



Major Components of Vapour Compression System

Refrigeration effect

- The change in enthalpy that occurs in the evaporator is called the **refrigeration effect**.
- This is the amount of heat that each kg of liquid refrigerant will absorb when it evaporates.
- In comparison, the same system without subcooling produces less refrigeration effect.



Major Components of Vapour Compression System

Evaporative Condensers

- Within evaporative condenser, the refrigerant flows through tubes and air is drawn or blown over the tubes by a fan.
- Water is sprayed on the tube surfaces.
- As the air passes over the coil, a small portion of the water evaporates.
- Evaporation of water absorbs heat from the coil that causes the refrigerant vapor within the tubes to condense.

Major Components of Vapour Compression System

Water-Cooled Condensers

- The shell-and-tube is the most common type.
- Water is pumped through the tubes while the refrigerant vapor fills the shell space surrounding the tubes.
- As heat is transferred from the refrigerant to the water, the refrigerant vapor condenses on the tube surfaces.
- Hot refrigerant vapour enters the water cooled condenser at the top
- The condensed liquid refrigerant then falls to the bottom of the shell at which is subcooled by the subcooler

Major Components of Vapour Compression System

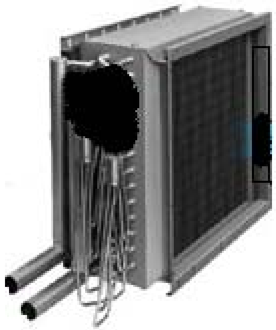
Evaporator.

- The evaporator is a heat exchanger that transfers heat from air, water, or some other fluid to the cool liquid refrigerant.
- Two common types of evaporators are finned-tube and shell-and-tube.

Major Components of Vapour Compression System

Finned-Tube Evaporators

- Includes rows of tubes passing through sheets of formed fins.
- Liquid refrigerant flows through the tubes, cools the tube and fin surfaces.
- When air passes through the coil and comes into contact with the cold fin surfaces, heat is transferred from the air to the refrigerant.



- Refrigerants boil and leave evaporator as vapor as heat is transferred.
- The fins of the coil are formed to produce turbulence as the air passes through that enhances heat transfer, preventing stratification within the coil-leaving airstream.
- Producing cooled air comparing with shell-and-tube type which is for chilled water.

Major Components of Vapour Compression System

Superheating

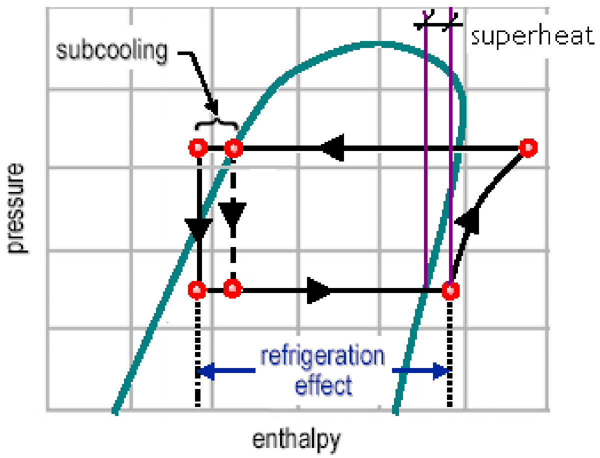
- Superheating occurs inside the final length of tubes at which temperature difference between refrigerant and air is highest

- Such large temperature difference increases the rate of heat transfer and the refrigerant vapor absorbs much heat.

- Liquid refrigerant completely evaporated

- Superheating shifts from the liquid/vapor region to vapor

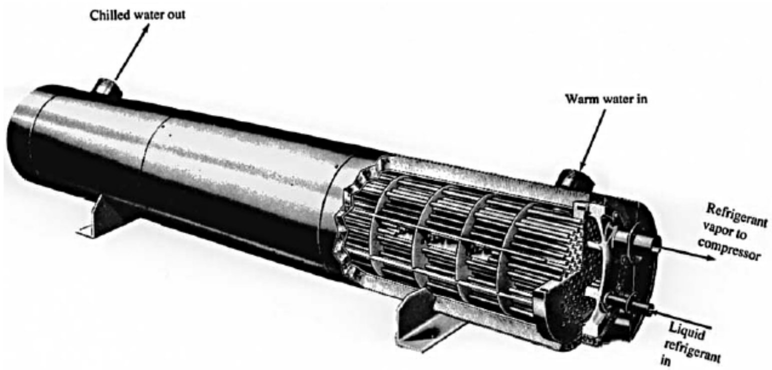
- It ensures the refrigerant vapor is completely free liquid before entering the compressor.



Major Components of Vapour Compression System

Shell-and-Tube Evaporators

- The cool liquid refrigerant flows through the tubes and water fills the shell space surrounding the tubes.
- As heat is transferred from the water to the refrigerant, the refrigerant boils inside the tubes.
- Baffles within the shell direct the water in a rising and falling flow path over the tubes that carry the refrigerant. This creates turbulence and results in improved heat transfer.



Major Components of Vapour Compression System

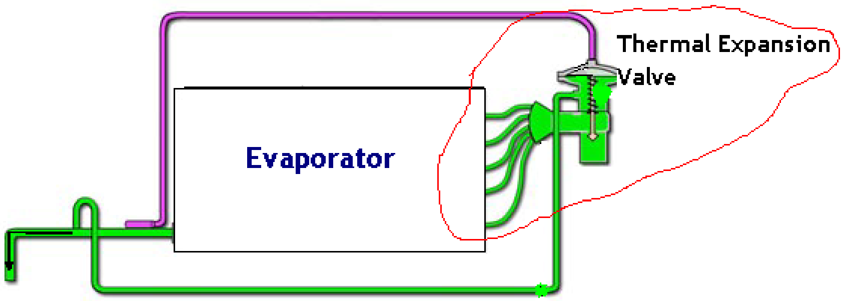
<u>Thermostatic expansion valve (TEV)</u>

This is an automatic valve that controls the rate of liquid refrigerant flow to the evaporator

Try to maintain a predetermined degree of superheat at the evaporator outlet to ensure that only gas is pumped and that no liquid enters the compressor that may cause serious mechanical damage to the compressor.

A TEV attempts to maintain a constant superheat at all times.

When there is less heat input to the evaporator, less superheat is generated and hence causing close of the valve bringing about an increase in superheat back to the design value with a corresponding decrease in pressure and vice versa.



Major Components of Vapour Compression System

<u>Capillary tube (Expansion device)</u>

This device has a fixed restriction usually in the form of a small-bore tube.

The drop in pressure being determined by the length and diameter of the tube.

These devices do not require potentially inefficient superheating in the evaporator.

They do not allow for any adjustment of superheat levels.

Major Components of Vapour Compression System

Solenoid Valve

- A solenoid valve is used to stop the flow of refrigerant within the system.
- These valves are magnetically operated, and an electric winding controls the opening and closing of the valve.
- The valve is typically a normally-closed type so that it is closed when deenergized.

Major Components of Vapour Compression System

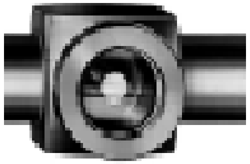
Moisture-Indicating Sight Glass

A moisture-indicating sight glass is installed in the liquid line, upstream of the expansion valve,

It enables the operator to observe the condition of the Refrigerant:

- Indicate its moisture &
- Detect the presence of bubbles in the liquid line

prior to entering the expansion valve.

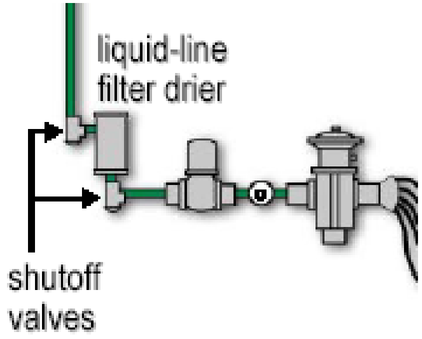


Sight Glass

Major Components of Vapour Compression System

Shut off Valve

- Shut off valves are used to isolate one part of the refrigeration system from the rest.
- They can be used to trap the refrigerant charge in one component of the system, the condenser for example, to permit service or repair to another part of the system.



Major Components of Vapour Compression System

Refrigerant piping design

Refrigeration system involving field-assembled refrigerant piping to connect components, system reliability and installed cost should be taken into consideration.

Design of the interconnecting refrigerant piping shall meet the following criteria:

- Return oil to the compressor at the proper rate, at all operating conditions
- Ensure that only liquid refrigerant (no vapor) enters the expansion device
- Minimize system capacity loss that is caused by pressure drop through the piping and accessories
- Minimize the total refrigerant charge in the system to improve reliability and

Major Components of Vapour Compression System

Return oil to the compressor at the proper rate

The first requirement is to ensure that oil is returned to the compressor at all operating conditions.

Oil is used to lubricate and seal the moving parts of a compressor.

The velocity of the refrigerant inside the discharge line must be high enough to carry the small oil droplets through the pipe to the condenser.

The velocity of the refrigerant vapor inside the suction line must be high enough to carry the droplets of oil through the pipe back to the compressor.

Without adequate velocity and proper pipe installation, oil may be trapped out in the system components.

Reduction oil level in the compressor could cause lubrication problems or even mechanical failure.

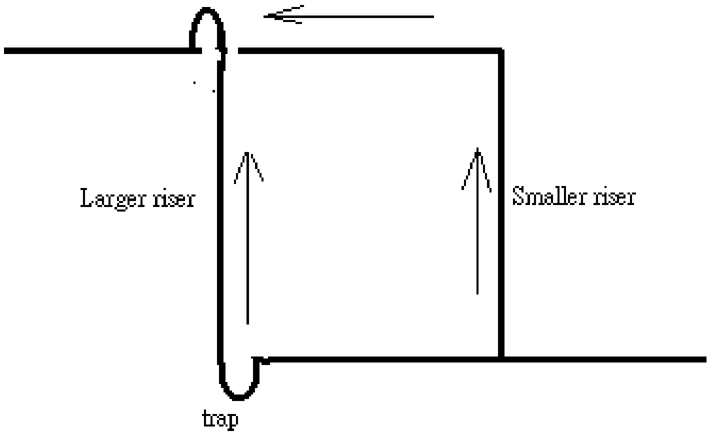
Major Components of Vapour Compression System

Return oil to the compressor at the proper rate

A double suction riser is installed in refrigeration circuit to cater for the system running at partial load, say less than 40% of maximum capacity

A double suction riser is constructed of a larger-diameter riser with a trap at the base and a smaller-diameter riser in parallel.

At maximum capacity, the refrigerant vapor flows up both risers at velocities that are adequate to carry the oil droplets.



Major Components of Vapour Compression System

Return oil to the compressor at the proper rate

At minimum capacity, the refrigerant velocity in the two risers becomes too low to carry the oil droplets.

The oil from both risers therefore drains down, filling the trap at the base of the larger riser.

When this trap becomes completely filled with oil, it prevents refrigerant vapor from flowing up the larger riser, and diverts all the refrigerant up the smaller riser.

This smaller riser is with a diameter small enough to maintain adequate velocity at minimum capacity.

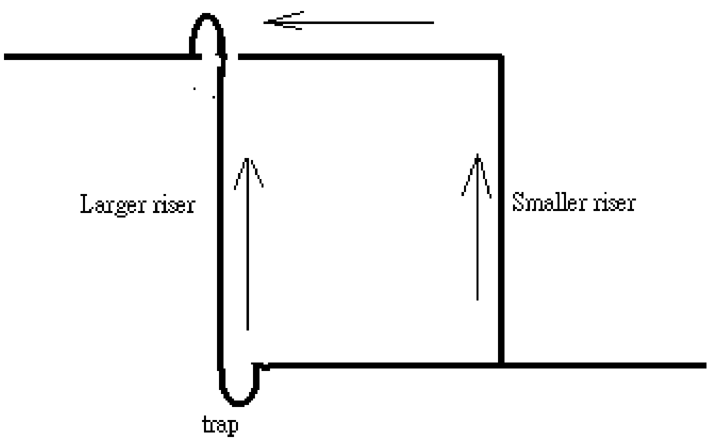
When system capacity is increased again, the higher refrigerant velocity clears the trap of oil, and refrigerant vapor again flows up both risers.

Major Components of Vapour Compression System

Return oil to the compressor at the proper rate

Notice the inverted trap at the top of the larger riser.

When the trap at the base of the larger riser is filled with oil, and refrigerant flows up only the smaller riser, this inverted trap prevents oil from draining back into the larger riser.



Major Components of Vapour Compression System

Piping materials for refrigerant pipes

Copper tubing is used for refrigerant piping in air-conditioning systems.

This tubing is available in various standard diameters and wall thickness.

The nominal diameter of the tubing is expressed in terms of its outside diameter.

The copper tubing should be completely free from dirt, scale, and oxide.

The piping system is constructed by brazing copper tubes and fittings together.

Major Components of Vapour Compression System

Procedures for Sizing of Pipes

Different pipe sizes for pipe line connecting compressor and condenser, condenser and expansion valve and evaporator and compressor. Pipe sizes could be in general determined as follows:

1) Determine the total length of piping.

2) Calculate the refrigerant velocity at both maximum and minimum system capacities.

3) Select the largest pipe diameter that will result in acceptable refrigerant velocity at both maximum and minimum capacities.

4) Calculate the total "equivalent" length of piping by adding the actual length of straight pipe to the equivalent length of any fittings to be installed in the pipe line.

Major Components of Vapour Compression System

Procedures for Sizing of Pipes

Determine the pressure drop (based on the total equivalent length) due to the straight pipe and fittings.

6) Add the pressure drop due to any accessories installed in the pipe line.

To begin with the process, the refrigerant piping should be routed in the shortest and simplest manner possible, minimizing the total length of piping. From the initial layout, the total measured length of the pipe line can be estimated.

Table (8.5) : Minimum Insulation Thickness for Outdoor Refrigerant Pipe

Minimum Thickness of Insulation for Refrigerant Pipe Installations (mm)									
Outdoor Condition at 35 °C, 95% RH; wind speed = 1m/s; h[3]=13.5									
	Fluid Operating Temperature								
Outer Diameter of Pipe(mm)[1]	0°C			-10°C			-20°C		
	Thermal Conductivity[2], λ			Thermal Conductivity[2], λ			Thermal Conductivity[2], λ		
	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.03	0.04
6	23	32	40	29	39	49	33	46	57
8	25	34	42	30	41	52	36	49	61
10	26	36	45	32	44	54	38	51	64
12	27	37	46	33	45	57	39	53	66
15	29	39	49	35	48	59	41	56	70
22	31	43	53	38	52	65	45	61	76
28	33	45	56	40	55	69	48	64	80
35	35	48	59	42	58	72	50	68	85
42	36	49	62	44	60	75	52	71	88
54	38	52	65	46	64	80	55	75	93
76	41	56	70	50	69	86	59	80	101

Note : (1) The table assumes pipes to be copper pipe of BS2871 : Part 1. For other metal pipes, same insulation thickness is applied to comparable outer diameters.

(2) Insulation thickness is based on thermal conductivity rated at 20°C mean.

(3) The surface coefficient h=13.5 is assumed for cement or black matt surfaces at outdoor condition with a wind speed of 1m/s.

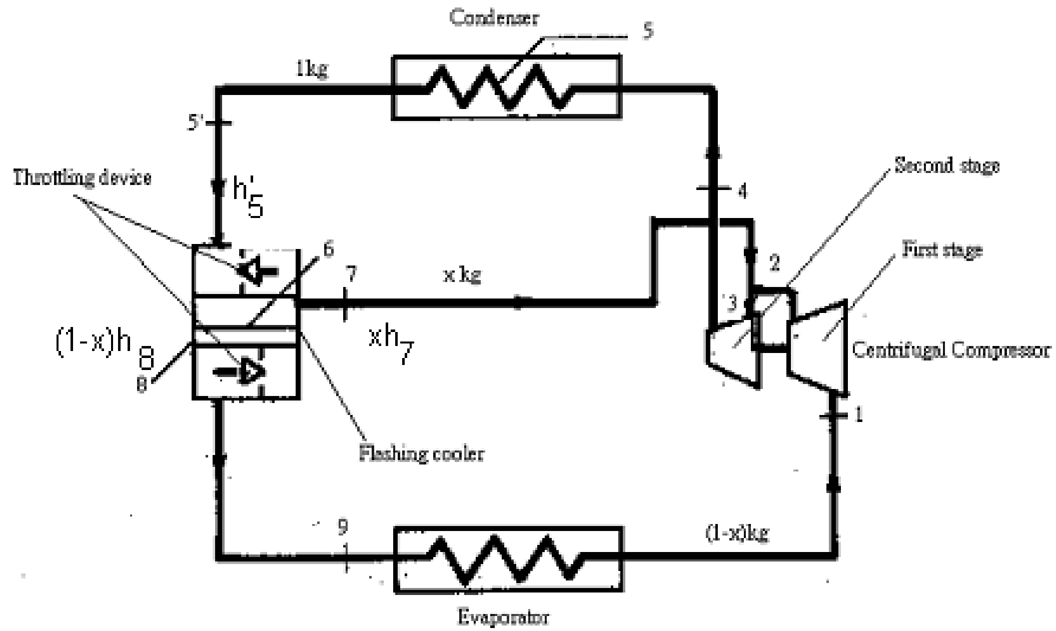
Two-stage vapor compression system

Two-stage vapor compression system

Consists of two stage of compression system

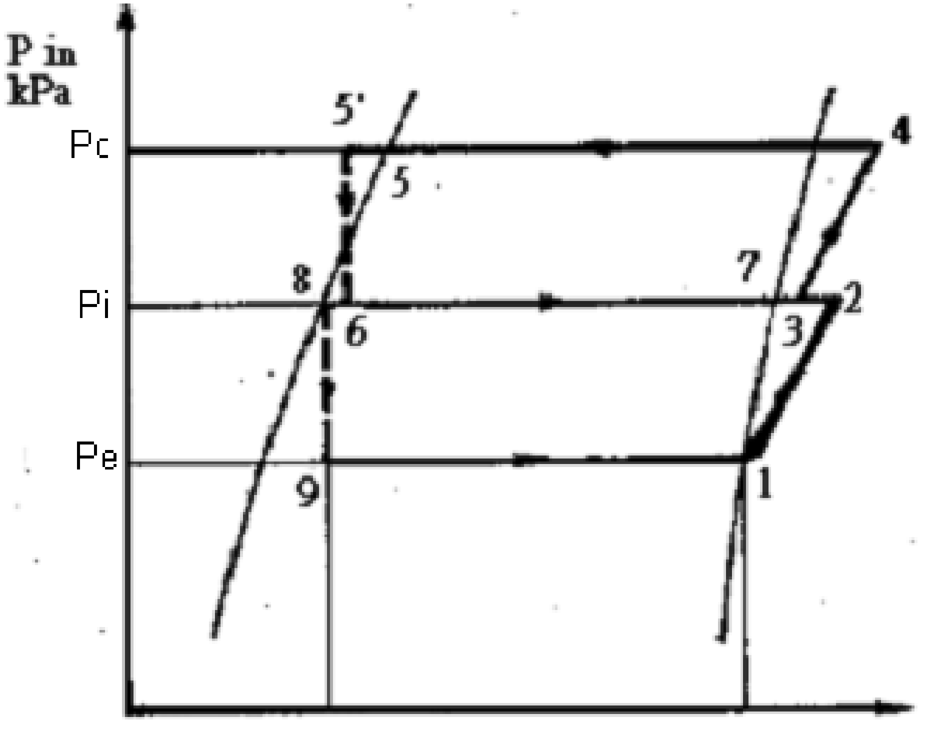
Comprise with a high stage compressor and a low stage compressor or several single stage compressors in series.

The pressure between the discharge pressure of the high stage and suction pressure of the low stage is called inter-stage pressure.



Two stage compound system with a flash cooler

Two-stage vapor compression system



Two stage compound system with a flash cooler

Two-stage vapor compression system

Defining the volumetric efficiency and compression ratio

$$\text{Volumetric efficiency} = \frac{\text{Volume of free air delivery}}{\text{Swept volume of the cylinder of the compressor}}$$

$$\text{Compression ratio} = \frac{\text{Pressure after the compression process}}{\text{Pressure before the compression process}}$$

Two-stage vapor compression system

Advantage of using two-stage vapour compression system compared with a single stage system:

1) The compression ratio of each stage in a two-stage system can be reduced so that the volumetric efficiency can be increased.

2) In two-stage system, the liquid refrigerant can be sub-cooled to the saturation temperature at the inter-stage pressure which in turn increases the refrigeration effect.

3) In two-stage system, the discharge gas from the low stage compressor can be de-superheated that results in reduction of discharge temperature after the high stage compression process.

Disadvantage of multi-stages systems include:

1) The complicated equipment results in high equipment cost comparing with single stage system.

Two-stage vapor compression system

Compound System – one type of 2-stage compression system

Vapor refrigerant at state point (1) enters the first stage of the compressor in dry saturated state.

This vapor is compressed to the inter-stage pressure Pi at stage point (2)

The mixture enters the second stage of compressor at state point(3)

Hot gas compressed to condensing pressure Pc leaves compressor at state point (4)

The hot gas is then discharged to the condenser and condenses into liquid state at state point (5).

Two-stage vapor compression system

Compound System (cont'd)

Upon passing the condenser, the sub-cooled liquid refrigerant at state point (5') flows through the high pressure side flow control device. A portion of liquid refrigerant evaporates into the vapor form in the flash cooler at state point (7)

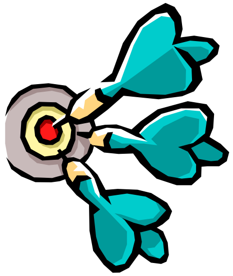
The flashed refrigerant cools the remaining portion of liquid refrigerant to the saturated temperature at state point (8) at the inter-stage pressure.

The mixture of liquid and vapor refrigerant in flash cooler is at state point (6).

Liquid refrigerant flows through low pressure expansion valve, a small amount of which is pre-flashed and the liquid vapor mixture enters the evaporator at state point (9).

In the evaporator, all liquid refrigerant is evaporated into vapor form and flows to the first stage inlet.

Two-stage vapor compression system



The inter-stage pressure of 2-stage compound system

1) The inter-stage pressure is selected such that the compression ratios at various stages are approximately equal.
2) The inter-stage pressure could be approximated by the following equation:

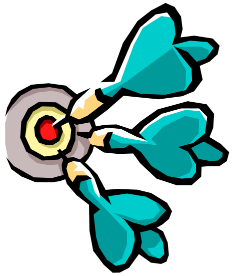
$$p_i = \sqrt{P_{cond} P_{evap}}$$

where

P_{cond} = Pressure of condenser and

P_{evap} = Pressure of evaporator

Two-stage vapor compression system

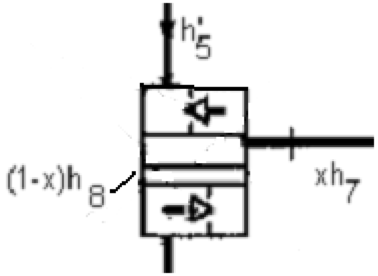


Defining the enthalpy of various state points in the PH diagram:

h_1	=	Enthalpy of saturated vapor leaving the evaporator
h_2	=	Enthalpy of superheated gas at the exit from the first stage compression
h_3	=	Enthalpy of mixture of the super-heated gas from the first-stage compressor and vapor refrigerant from the flash cooler
h_4	=	Enthalpy of the hot gas discharged from the second stage compression
h_5'	=	Enthalpy of sub-cooled liquid refrigerant leaving the condenser
h_6	=	Enthalpy of refrigerant after the throttling device
h_7	=	Enthalpy of saturated liquid refrigerant at the inter-stage pressure pi
h_8	=	Enthalpy of saturated vapor refrigerant at the inter-stage pressure pi
h_9	=	Enthalpy of refrigerant entering the evaporator

The portion of flashed vapour refrigerant in the flash cooler

In the flash cooler, there is x kg of vaporized refrigerant cools down the remaining liquid refrigerant (1-x) kg to the saturation temperature at the inter-stage pressure.
From the heat balance point of view, we have



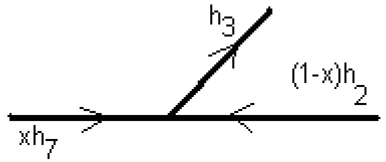
$$h_5' = xh_7 + (1-x)h_8$$

Note that x is also the dryness fraction of the liquid-vapor mixture in the flash cooler at the inter-stage pressure. This equation could be expressed as

$$x = \frac{h_5' - h_8}{h_7 - h_8}$$

Enthalpy of vapor mixture entering the second-stage compressor

Heat balance at the mixing point before entering the second stage compressor could be show as follows:-



Two-stage vapor compression system

Coefficient of Performance of the 2-stage compound system with a flash cooler

The refrigeration effect in evaporator Qre (per kg of refrigerant through condenser) could be expressed as:-

$Qre = (1-x)(h1-hg)$

Work input Win to the compressor (first and second stages)

It could be expressed as

$W_{in} = (1-x)(h_2-h_1) + (h_4-h_3)$

Heat Pumps

A heat pump extracts heat from a heat source and rejects heat to air or water at a higher temperature.

During summer, the heat extraction, or refrigeration effect, is the useful effect for cooling.

In winter the rejected heat alone, or rejected heat plus supplementary heating from a heater form the useful effect for heating.

A heat pump is a packaged air conditioner or a packaged unit with a reversing valve or other changeover setup.

A heat pump has all the main components of an air conditioner or package unit: fan, filters, compressor, evaporator, condenser, and a throttling device.

Heat Pumps

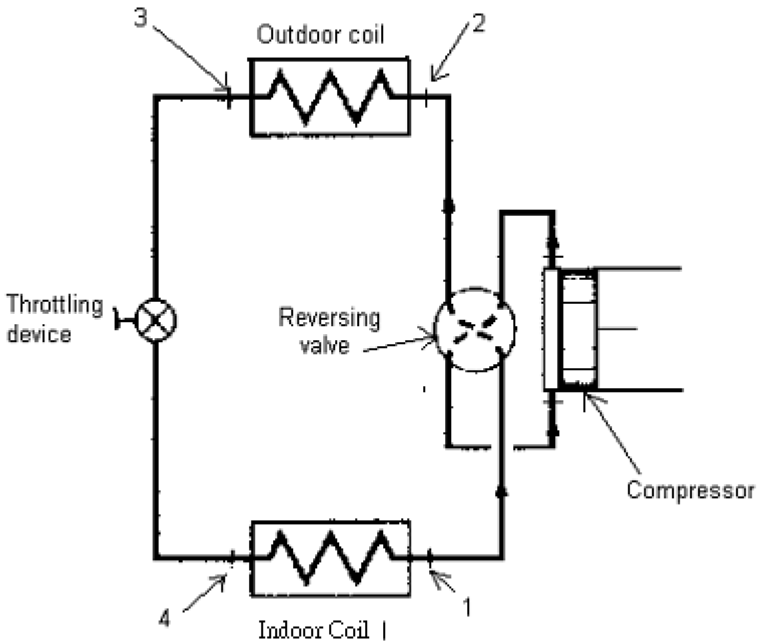
The apparatus for changing from cooling to heating or vice versa is often a reversing valve, in which the refrigerant flow to the condenser is changed to the evaporator.

Alternatively, air passage through the evaporator may be changed over to passage through the condenser.

A supplementary heater is often provided when the heat pump capacity does not meet the required output during low outdoor temperatures.

R-22 and R-134a are the most widely used halocarbon refrigerants in new heat pumps.

Heat Pumps



Heat Pump Cycle

Heat Pumps

Heat Pump Cycle

A heat pump cycle comprises the same processes and sequencing order as a refrigeration cycle except that both the refrigeration effect q_{ref}, and the heat pump effect q_{hp} in are the useful effects,

The coefficient of performance of a refrigeration system: -

$$COP_{ref} = \frac{h_1 - h_4}{w_{in}} = \frac{q_{1,4}}{w_{in}}$$

where $h_4, h_1 =$ Enthalpy of refrigerant entering & leaving the evaporator

$w_{in} =$ work input

The coefficient of performance of the heat effect :-

$$COP_{hp} = \frac{q_{2,3}}{w_{in}}$$

Heat Pumps

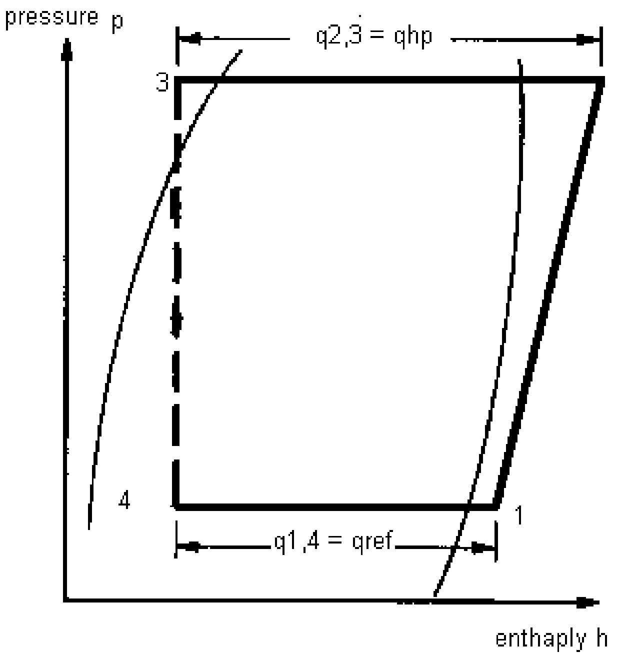
Useful heating effect could be found by the following equation :

$$q_{2,3} = (h_2 - h_3)$$

where h_2 = enthalpy of hot gas discharged from compressor

where h_3 = enthalpy of the sub-cooled liquid leaving the condenser

PH diagram



Vapor Absorption Cycle

The following illustrates the refrigeration cycle using vapour absorption by LiBr solution.

Water is the refrigerant in the cycle.

Distilled water is stable, nontoxic, low in cost, readily available, environmentally friendly, and has a relatively high heat of vaporization

The cycle shall be operated in a vacuum, that is, at a pressure below atmospheric pressure.

Large quantities of water are absorbed by the absorbent and separated within the absorption cycle.

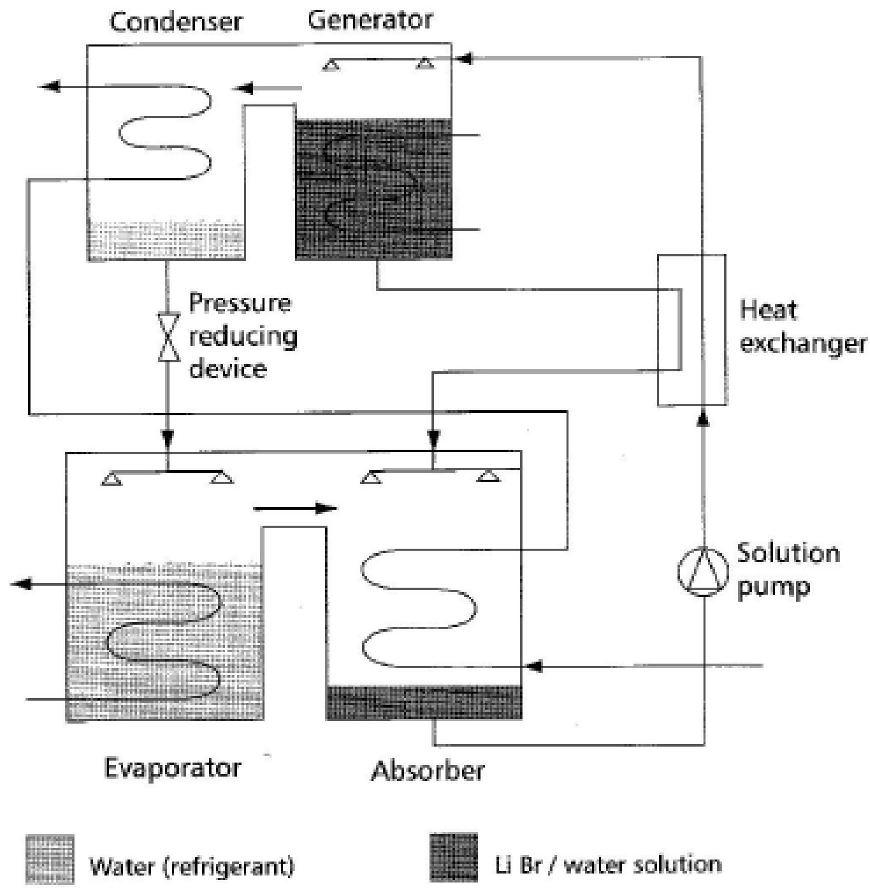
Vapor Absorption Cycle

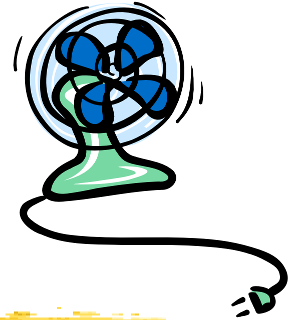
In the evaporator the refrigerant extracts heat by evaporation

Refrigerant vapour is absorbed and condensed into solution in the absorber, thereby making the solution weaker.

The weak solution is pumped to high pressure and transferred to the generator

The addition of heat in the generator raises the temperature of the solution, separating and evaporating the refrigerant, thus making the solution stronger.



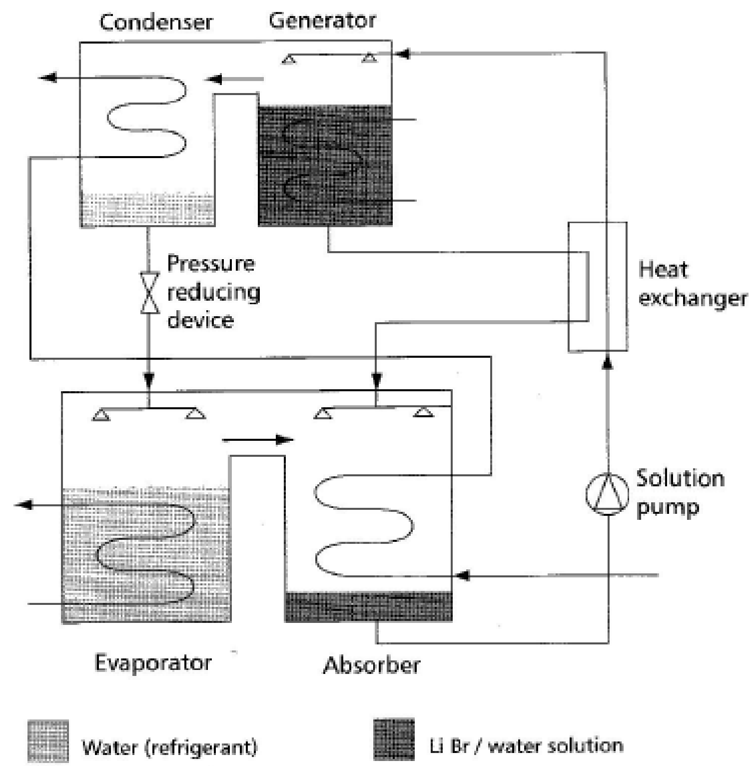


Vapor Absorption Cycle

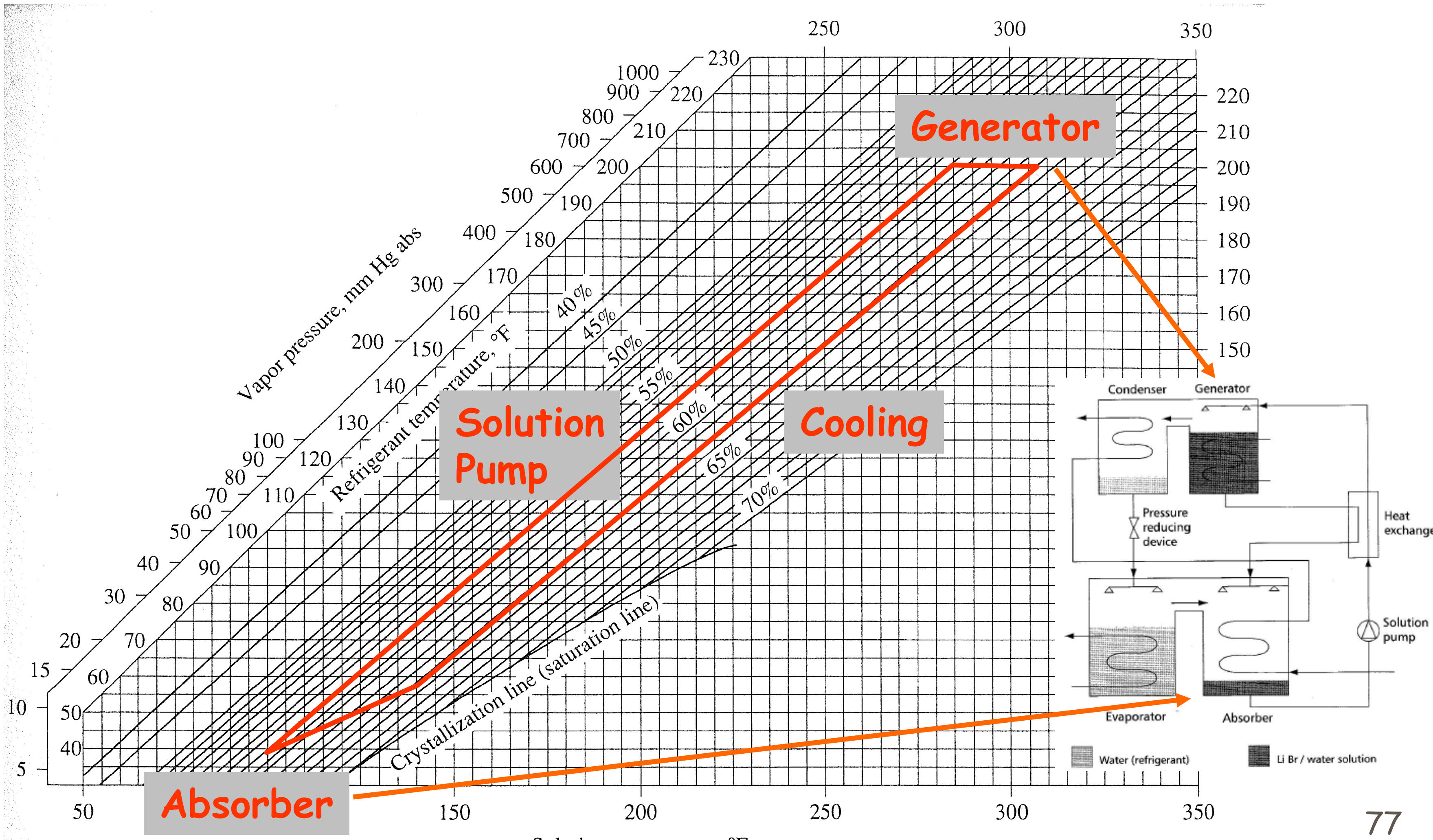
The strong solution is returned to the absorber through the pressure reducing device so maintaining the pressure difference between the high and low sides of the system

The refrigerant vapour driven out of solution at high pressure in the generator flows to the condenser where it is liquefied by removal of heat at constant pressure

The condensed liquid is fed through a pressure reducing device into the evaporator where the cycle re-commences.



Vapor Absorption Cycle



Q & A