Chapter 5. Thermal Engineering-2

Thermal systems Applications

Refrigeration systems, Air conditioning systems, pumps, blowers and compressors, and their working principles and specifications.

STUDY MATERIAL FOR CHAPTER 5:

CHAPTER 5:

Turbines and Internal combustion engines are power developing thermal systems where as Refrigeration, air conditioning systems , pumps, blowers and compressors are power consuming devices.

PUMPS:

There are two broad categories of turbomachinery, pumps and turbines. The word pump is a general term for any fluid machine that adds energy to a fluid. Some authors call pumps **energy absorbing devices** since energy is supplied *to* them, and they transfer most of that energy to the fluid, usually via a rotating shaft (Fig. 5.1*a*). The increase in fluid energy is usually felt as an increase in the pressure of the fluid. Turbines, on the other hand, are **energy producing devices**—they extract energy *from* the fluid and transfer most of that energy to some form of mechanical energy output, typically in the form of a rotating shaft (Fig.5.1*b*).

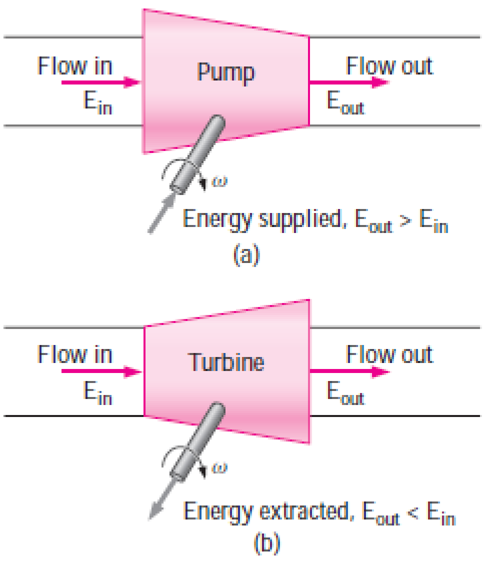


Figure 5.1: (a) A pump supplies energy to a fluid, while (b) a turbine extracts energy from a fluid.

The fluid at the outlet of a turbine suffers an energy loss, typically in the form of a loss of pressure. An ordinary person may think that the energy supplied to a pump increases the speed of fluid passing through the pump and that a turbine extracts energy from the fluid by slowing it down. This is not necessarily the case. Consider a control volume surrounding a pump (Fig. 5.2).

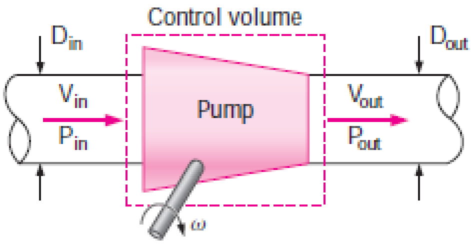


Figure 5.2 : For the case of steady flow, conservation of mass requies that the mass flow rate out of the pump must equal the mass flow rate into the pump; for incompressible flow with equal inlet and outlet cross-secional areas (D_{out} = D_{in}) , we conclude that V_{out} =V_{in} , P_{out} >P_{in}.

We assume steady conditions. By this we mean that neither the mass flow rate nor the rotational speed of the rotating blades changes with time. (The detailed flow field near the rotating blades inside the pump is *not* steady of course, but control volume analysis is not concerned with details inside the control volume.) By conservation of mass, we know that the mass flow rate into the pump must equal the mass flow rate out of the pump. If the flow is incompressible, the volume flow rates at the inlet and outlet must be equal as well. Furthermore, if the diameter of the outlet is the same as that of the inlet, conservation of mass requires that the average speed across the outlet must be identical to the average speed across the inlet. In other words, the pump does not necessarily increase the *speed* of the fluid passing through it; rather, it increases the *pressure* of the fluid. Of course, if the pump were turned off, there might be no flow at all. So, the pump *does* increase fluid speed compared to the case of no pump in the system. However, in terms of changes from the inlet to the outlet *across* the pump, fluid speed is not necessarily increased. (The output speed may even be *lower* than the input speed if the outlet diameter is larger than that of the inlet.)

The purpose of a pump is to add energy to a fluid, resulting in an increase in fluid pressure, not necessarily an increase of fluid speed across the pump.

An analogous statement is made about the purpose of a turbine:

The purpose of a turbine is to extract energy from a fluid, resulting in a decrease of fluid pressure, not necessarily a decrease of fluid speed across the turbine.

Fluid machines that move liquids are called **pumps,** but there are several other names for machines that move gases (Fig. 5.3).

A **fan** is a gas pump with relatively low pressure rise and high flow rate. Examples include ceiling fans, house fans, and propellers.
A **blower** is a gas pump with relatively moderate to high pressure rise and moderate to high flow rate. Examples include centrifugal blowers and squirrel cage blowers in automobile ventilation systems, furnaces, and leaf blowers.
A **compressor** is a gas pump designed to deliver a very high pressure rise, typically at low to moderate flow rates. Examples include air compressors that run pneumatic tools and inflate tires at automobile service stations, and refrigerant compressors used in heat pumps, refrigerators, and air conditioners.

	Fan	Blower	Compressor
ΔP	Low	Medium	High
$\dot{V}$	High	Medium	Low

Figure 5.3: When used with gases, pumps are called fans, blowers or compressors, depending on the relative values of pressure rise and volume flow rate.

Pumps and turbines in which energy is supplied or extracted by a rotating shaft are properly called turbomachines, since the Latin prefix turbo means "spin." Not all pumps or turbines utilize a rotating shaft, however. The hand-operated air pump you use to inflate the tires of your bicycle is a prime example (Fig. 5.4 a). The up and down reciprocating motion of a plunger or piston replaces the rotating shaft in this type of pump, and it is more proper to call it simply a fluid machine instead of a turbomachine. An old-fashioned well pump operates in a similar manner to pump water instead of air (Fig. 5.4 b). Nevertheless, the words turbomachine and turbomachinery are often used in the literature to refer to all types of pumps and turbines regardless of whether they utilize a rotating shaft or not.

(a) (b)

Figure 5.4: Not all pumps have a rotating shaft; (a) energy is supplied to this manual tyre pump by the up and down motion of a person's arm to pump air; (b) a similar mechanism is used to pump water with an old –fashioned well pump.

Fluid machines may also be broadly classified as either positive-displacement machines or dynamic machines, based on the manner in which energy transfer occurs. In positive-displacement machines, fluid is directed into a closed volume. Energy transfer to the fluid is accomplished by movement of the boundary of the closed volume, causing the volume to expand or contract, thereby sucking fluid in or squeezing fluid out, respectively. Your heart is a good example of a positive-displacement pump (Fig. 5.5a). It is designed with one-way valves that open to let blood in as heart chambers expand, and other one-way valves that open as blood is pushed out of those chambers when they contract. An example of a positive-displacement turbine is the common water meter in your house (Fig. 5.5b), in which water forces itself into a closed chamber of expanding volume connected to an output shaft that turns as water enters the chamber. The boundary of the volume then collapses, turning the output shaft some more, and letting the water continue on its way to your sink, shower, etc. The water meter records each 360° rotation of the output shaft, and the meter is precisely calibrated to the known volume of fluid in the chamber.

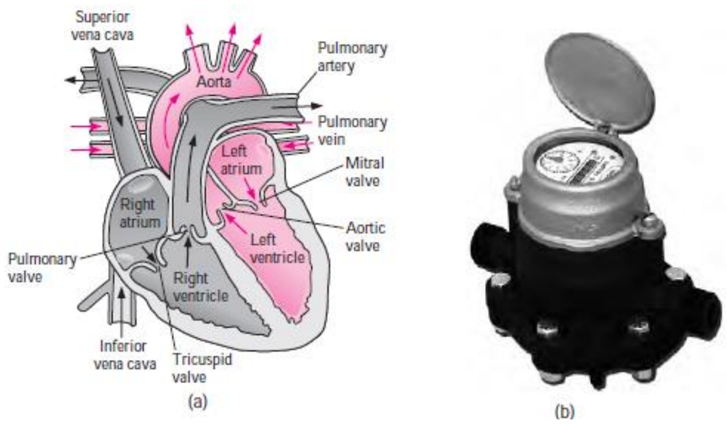


Figure 5.5: (a) The human heart is an example of a positive displacement pump; blood is pumped by expansion and contraction of heart chambers called ventricles. (b) The common water meter in your house is an example of a positive displacement turbine; water fills and exits a chamber of known volume for each revolution of the output shaft.

In dynamic machines, there is no closed volume; instead, rotating blades supply or extract energy to or from the fluid. For pumps, these rotating blades are called impeller blades, while for turbines, the rotating blades are called runner blades or buckets. Examples of dynamic pumps include enclosed pumps and ducted pumps (those with casings around the blades such as the water pump in your car's engine), and open pumps (those without casings such as the ceiling fan in your house, the propeller on an airplane, or the rotor on a helicopter). Examples of dynamic turbines include enclosed turbines, such as the hydroturbine that extracts energy from water in a hydroelectric dam, and open turbines such as the wind turbine that extracts energy from the wind (Fig. 5.6).

Figure 5.6: A wind turbine is a good example of a dynamic machine of the open type; air turns the blades, and the output shaft drives an electric generator.

Figure 5.7: Centrifugal monoblock pump is a good example of a dynamic machine of a closed type; motor drives the shaft carrying the blades which transfers the energy to the Liquid being pumped.

Positive displacement Pumps

Examples of Positive displacement pumps:

Lobe pump, gear pump, scroll pump, cavity pump/ conveyor, Peristaltic Pump, Reciprocating pump,

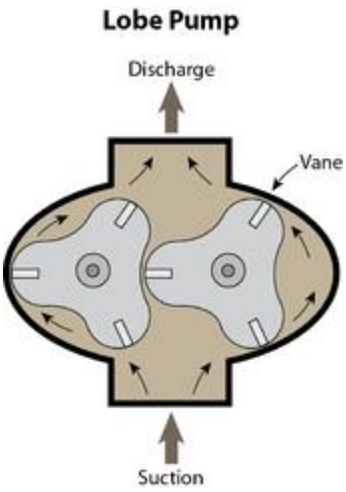


Figure 5.8: Lobe pump

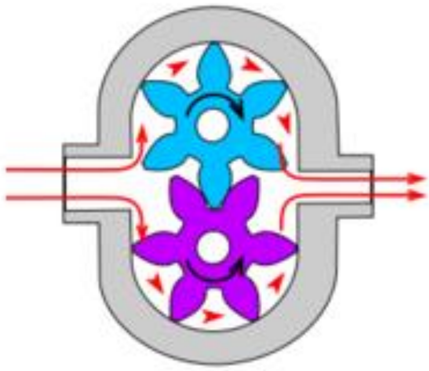


Figure 5.9: Gear pump

Figure 5.10: Scroll pump

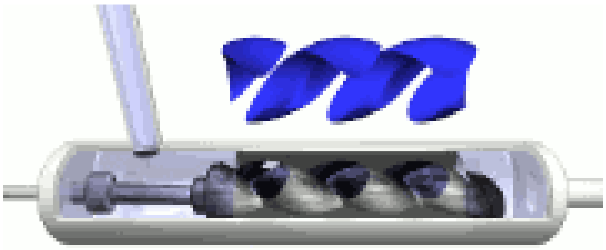


Figure 5.11: Cavity pump

Figure 5.12:360 Degree Peristaltic Pump

Figure5.13: Reciprocating pump

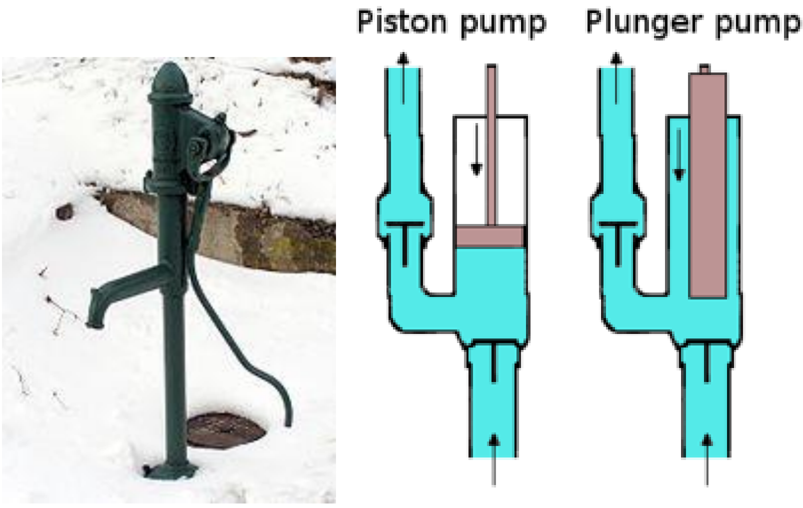


Figure 5.14: Piston Pump and plunger pump

Dynamic machines: Centrifugal pump

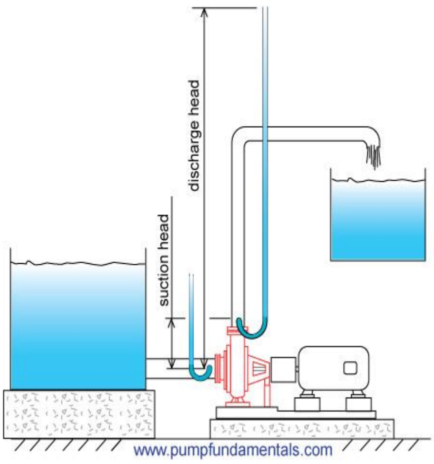


Figure 5.15: The pumping system

Centrifugal pumps basically consist of a stationary pump casing and an impeller mounted on a rotating shaft. The pump casing provides a pressure boundary for the pump and contains channels to properly direct the suction and discharge flow. The pump casing has suction and discharge penetrations for the main flow path of the pump and normally has small drain and vent fittings to remove gases trapped in the pump casing or to drain the pump casing for maintenance.

Figure 5.16 is a simplified diagram of a typical centrifugal pump that shows the relative locations of the pump suction, impeller, volute, and discharge. The pump casing guides the liquid from the suction connection to the center, or eye, of the impeller. The vanes of the rotating impeller impart a radial and rotary motion to the liquid, forcing it to the outer periphery of the pump casing where it is collected in the outer part of the pump casing called the volute. The volute is a region that expands in cross-sectional area as it wraps around the pump casing. The purpose of the volute is to collect the liquid discharged from the periphery of the impeller at high velocity and gradually cause a reduction in fluid velocity by increasing the flow area. This converts the velocity head to static pressure. The fluid is then discharged from the pump through the discharge connection.

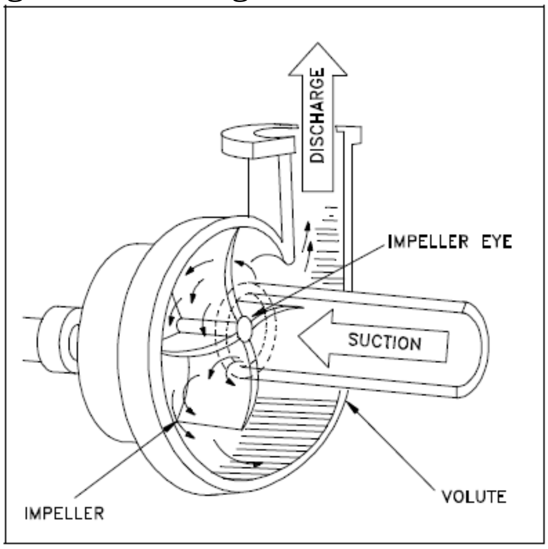


Figure :5.16: Cut sectional view of a centrifugal pump.

<u>Important point to be note:</u> Pumps handle liquids and compressors handle gases; there are no machines which can handle both liquid and gases.

Compressors:

Air compressor:

The purpose of an air compressor is to provide a continuous supply of pressurized air.

Air compressors of various designs are used widely throughout DOE facilities in numerous applications. Compressed air has numerous uses throughout a facility including the operation of equipment and portable tools. ***Three types of designs include reciprocating, rotary, and centrifugal air compressors.***

<u>Centrifugal air compressor:</u>

The centrifugal compressor, originally built to handle only large volumes of low pressure gas and air (maximum of 40 psig), has been developed to enable it to move large volumes of gas with discharge pressures up to 3,500 psig. However, centrifugal compressors are now most frequently used for medium volume and medium pressure air delivery. One advantage of a centrifugal pump is the smooth discharge of the compressed air. The centrifugal force utilized by the centrifugal compressor is the same force utilized by the centrifugal pump. The air particles enter the eye of the impeller, designated D in Figure 15.17. As the impeller rotates, air is thrown against the casing of the compressor. The air becomes compressed as more and more air is thrown out to the casing by the impeller blades. The air is pushed along the path designated A, B, and C in Figure 5.17. The pressure of the air is increased as it is pushed along this path. Note in Figure 5.17 that the impeller blades curve forward, which is opposite to the backward curve used in typical centrifugal liquid pumps. Centrifugal compressors can use a variety of blade orientation including both forward and backward curves as well as other designs.

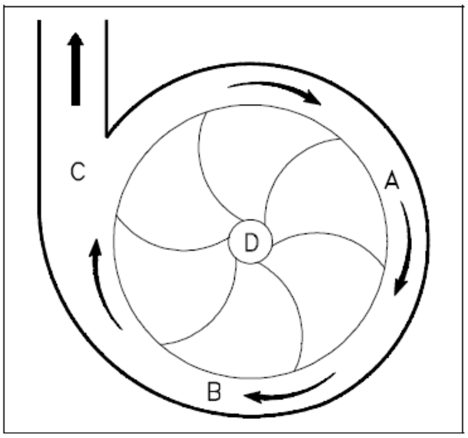


Figure: 15.17: Simplified centrifugal compressor

There may be several stages to a centrifugal air compressor, as in the centrifugal pump, and the result would be the same; a higher pressure would be produced. The air compressor is used to create compressed or high pressure air for a variety of uses. Some of its uses are pneumatic control devices, pneumatic sensors, pneumatic valve operators, pneumatic motors, and starting air for diesel engines.

Refrigeration system:

REFRIGERATION SYSTEMS:

Introduction:

One of the major application area of thermodynamics is *refrigeration*, which is the transfer of heat from a lower temperature region to a higher temperature region. Devices that produce refrigeration are called *refrigerators,* and the cycles on which they operate are called *refrigeration cycles*. The most frequently used refrigeration cycle is the *vapor-compression refrigeration cycle* in which the refrigerant is vaporized and condensed alternately and is compressed in the vapor phase. For large scale cooling needs, the more economical and desirable system is vapour-absorption refrigeration system where the thermal energy can be directly used as a source of energy instead of using electrical energy as a major source of energy.

Refrigeration: *The art of producing and maintaining the temperature in an enclosed space below that of the surrounding temperature by continuously extracting the heat from it, is known as refrigeration.* In order to maintain the low temperature in the refrigerated space, it is necessary to remove heat continuously equal to the amount of heat leaking into the enclosed space and reject the same to the surrounding atmosphere at higher temperature.

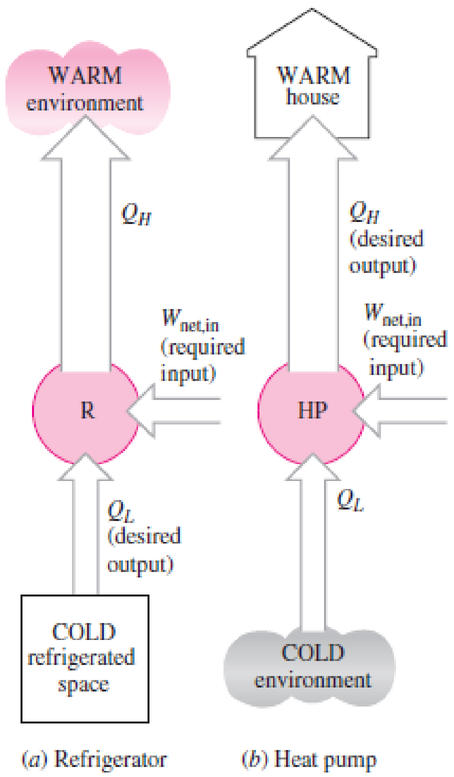


Figure : The objective of a refrigerator is to remove heat (*QL*) from the cold medium; the objective of a heat pump is to supply heat (*QH*) to a warm medium.

We all know from experience that heat flows in the direction of decreasing temperature, that is, from high-temperature regions to low-temperature. This heat-transfer process occurs in nature without requiring any devices. The reverse process, however, cannot occur by itself. The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators.** Refrigerators are cyclic devices, and the working fluids used in the refrigeration cycles are called **refrigerants.**

A refrigerator is shown schematically in Fig.1a. Here Q_L, is the magnitude of the heat removed from the refrigerated space at temperature T_L, Q_H is the magnitude of the heat rejected to the warm space at temperature T_H, and $W_{net,in}$ is the net work input to the refrigerator.

Q_L and Q_H represent magnitudes and thus are positive quantities. Another device that transfers heat from a low-temperature medium to a high-temperature one is the **heat pump.**

Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only. The objective of a refrigerator is to maintain the refrigerated space at a low temperature by removing heat from it. Discharging this heat to a higher-temperature medium is merely a necessary part of the operation, ***not the purpose.*** The objective of a heat pump, however, is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low-temperature source, such as well water or cold outside air in winter, and supplying this heat to a warmer medium such as a house (Fig. 1 *b*).

Principle of Refrigeration: *It is based on the second law of thermodynamics, which states that heat can be made to flow from a body at* *lower temperature to a body at higher temperature with the help of external energy source. Hence it is also called as a reversed heat engine.*

The performance of refrigerators and heat pumps is expressed in terms of the **coefficient of performance** (COP), defined as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

Thus,

Coefficient of performance of refrigeration system is defined as a ratio of refrigerating effect to the input work required to produce the effect.

Coefficient of performance of Heat Pump is defined as a ratio of heating effect to the input work required to produce the effect.

These relations can also be expressed in the rate form by replacing the quantities Q_L, Q_H, and $W_{net,in}$ by $\dot{Q}_L$, $\dot{Q}_H$ and $\dot{W}_{net.in}$, respectively. Notice that both COP_R and COP_{HP} can be greater than 1.

As $Q_H = Q_L + W_{net.in}$, it implies that

$$COP_{HP} = COP_R + 1$$

for fixed values of Q_L and Q_H. This relation implies that $COP_{HP} > 1$ since COP_R is a positive quantity.

The *cooling capacity* of a refrigeration system—that is, the rate of heat removal from the refrigerated space—is often expressed in terms of **tons of refrigeration.** *The capacity of a refrigeration system that can freeze 1 ton (2000 lbm) of liquid water at 0°C (32°F) into ice at 0°C in 24 h is said to be 1 ton.*

One ton of refrigeration is equivalent to 211kJ/min.

The cooling load of a typical 200-m^2 residence is in the 3-ton (10-kW) range.

Refrigerator: *A machine used to remove heat continuously from a refrigerated space and to reject it to the atmosphere.*

Refrigerant: *It is the working fluid (liquids or gases) used in refrigerators. Examples: Ammonia (NH_3), Methyl Chloride (CH_3Cl), Freon-12(CCl_2F_2), Freon-13, Freon-22, Carbon-dioxide (CO_2), Sulphur dioxide (SO_2), Brine, Air, water, etc.*

Ice-Making Capacity: *It is the capacity of a refrigerating system to make ice, starting from water at room temperature.*

Relative COP: *It is defined as the ratio of actual COP to the theoretical COP.*

1) Vapor-Compression Refrigeration System:

Parts of a Vapor-compression Refrigeration system:
The essential elements required to accomplish the refrigerating process and make up the refrigerator system are:
1. Evaporator   2. Compressor   3. Condenser   4. Expansion valve

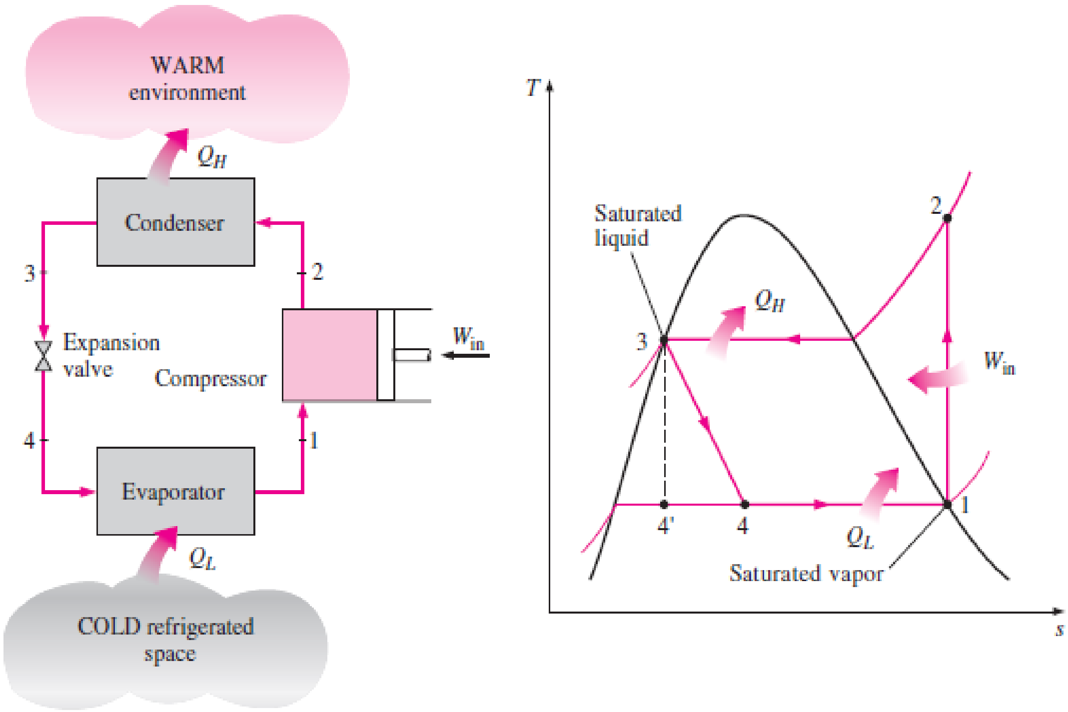
1. Evaporator: It is also called as the cooling unit, chilling unit or freezing unit. Evaporator is the part of a refrigerator where substance which are to be cooled are kept and the liquid refrigerant is evaporated by the absorption of heat from the refrigerator cabinet. It consists of metal tube in the form of coil kept in the refrigerated space. The purpose of this coil is to provide more surface area over which the medium can come in contact and at the same time, passage through which refrigerant can flow. The refrigerant in the form of liquid enters the evaporator, absorbs heat from the medium and will gradually change from liquid to vapour.

2. Compressor: The refrigerant from the evaporator is drawn at low pressure to the compressor, through suction valve and delivers it to the condenser through exhaust valve at high pressure and temperature. The main objective of the compressor is to increase the pressure of the working fluid to higher pressure, so that, corresponding to this high pressure the saturation temperature of the refrigerant should be slightly higher than the atmospheric temperature. This is necessary to reject heat in the condenser and to condense the refrigerant to saturated liquid. Refrigeration compressors are usually either rotary or reciprocating type and are driven by an electric motor.

3. Condenser: A condenser is an appliance in which the heat from the refrigerant is rejected to another medium, usually the atmospheric air or water. It is made of either finned tubing or tubing interlaced with wire, to increase the heat transfer area.
   The two main functions of the condenser are:
   (i) It transfers the latent heat of evaporation, which was absorbed by the refrigerant in the evaporator and the heat developed due to compression, to the surrounding air.
   (ii) It condenses the refrigerant vapour to a refrigerant liquid so that it can be reused in the refrigeration cycle.

4. Expansion Valve: An expansion valve serves as a device to reduce the pressure and temperature of the liquid refrigerant before it passes to the evaporator. The liquid refrigerant form the condenser is passed through an expansion valve where it reduces its pressure and temperature.

Working of Vapour Compression Refrigeration system:



1-2 Isentropic compression in a compressor
2-3 Constant-pressure heat rejection in a condenser
3-4 Throttling in an expansion device
4-1 Constant-pressure heat absorption in an evaporator

Fig: Schematic and *T*-*s* diagram for the ideal vapor-compression refrigeration cycle.

The refrigerant at low temperature and low pressure passing through the evaporator coils absorbs the latent heat of evaporation from the substances to be cooled and gets evaporated. Thus the temperature of the freezing chamber gets lowered. The evaporated low pressure refrigerant is drawn by compressor and compresses it to high pressure, so that corresponding to that high pressure, the saturation temperature of the refrigerant is higher than the temperature of the cooling medium (ambient air or water) in the condenser. Thus the high-temperature and high pressure vapour rejects heat to the cooling medium and gets condensed to saturated liquid in the condenser. At the exit of the condenser the saturated liquid refrigerant is ready to expand to low pressure and temperature. The high pressure, approximately room temperature liquid refrigerant flows to the throttle valve (expansion valve or a capillary tube) in which it expands to a low pressure and then ducted to the evaporator to repeat the cycle.

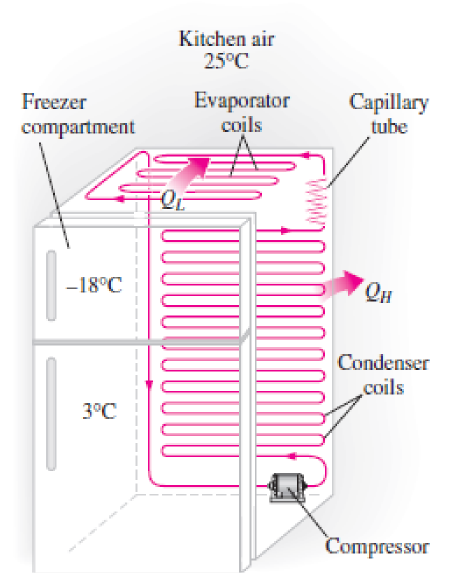


Figure: An ordinary household refrigerator.

The expansion valve lowers the pressure and temperature of the refrigerant, at the same time evaporates the refrigerant partly. Thus the refrigerant entering the evaporator will be a wet vapour and at a very low temperature of around -20°C.
To maintain the evaporator temperature with the desired limits, the motor driving the compressor is controlled by a thermostat switch.

Dichloro-difluro methane, popularly known as Freon-12, or R-12 is the most commonly used refrigerant.

Refrigerants commonly used in Practice:

The most commonly used refrigerants are:

1. Ammonia:- In vapour absorption refrigerators
2. Carbon-dioxide:- In marine refrigerators
3. Sulphur dioxide:- in household refrigerators
4. Methyl chloride:- in small scale refrigeration and domestic refrigerators
5. Freon-12:- In domestic vapour compression refrigerators
6. Freon-22:- in Air-conditioners

Properties of a good Refrigerant

The desirable properties of an ideal refrigerant can be grouped into four main types.

1) Thermodynamic properties
   (a) Boiling point
   (b) Freezing point
   (c) Evaporator and condenser pressure
   (d) Latent heat of Evaporation
2) Physical Properties
   (a) Specific Volume
   (b) Specific Heat
   (c) Viscosity
3) Safe working Properties
   a) Toxicity
   b) Flammability

c) Corrosiveness
d) Chemical Stability

4) Other properties
   a) COP
   b) Odour
   c) Leak
   d) Action with Lubricating Oil

1) Boiling point: An ideal refrigerant must have low boiling temperature at atmospheric pressure.

2) Freezing point: An ideal refrigerant must have a very low freezing point because the refrigerant should not freeze at low evaporator temperatures.

3) Evaporator and condenser Pressure: In order to avoid leakage of the atmospheric air and also to enable the detection of the leakage of the refrigerant, both the evaporator and condenser pressures should be slightly above the atmospheric pressure.

4) Latent heat of Evaporation: The latent heat of evaporation must be very high so that a minimum amount of refrigerant will accomplish the desired result; in other words, it increases the refrigeration effect.

5) Specific volume: The specific volume of the refrigerant must be very low. The lower specific volume of the refrigerant at the suction of the compressor reduces the size of the compressor.

6) Specific heat of liquid and vapour: A good refrigerant must have low specific heat when it is in liquid state and high specific heat when it is vaporised. The low specific heat of the refrigerant helps in sub-cooling of the liquid and high specific heat of the vapour helps in decreasing the superheating of the vapour. Both these desirable properties increase the refrigeration effect.

7) Viscosity: The viscosity of a refrigerant at both the liquid and vapour states must be very low as it improves the heat transfer and reduces the pumping pressure.

8) Toxicity: A good refrigerant should be non-toxic, because any leakage of the refrigerant poisons the atmosphere if it is toxic.

9) Corrosiveness: A good refrigerant should be non-corrosive to prevent the corrosion of the metallic parts of the refrigerators.

10) Chemical Stability: An ideal refrigerant must not decompose under operating conditions.

11) Coefficient of Performance: The coefficient of performance of a refrigerant must be high so that the energy spent in refrigeration will be less.

12) Odour: A good refrigerant must be odourless, otherwise some foodstuff such as meat, butter, etc. loses their taste.

13) Leakage tests: The refrigerant must be such that any leakage can be detected by simple tests.

14) Action with lubricating oil: A good refrigerant must not react with the lubricating oil used in lubricating the parts of the compressor.

Air conditioning Systems:

Refer K.R.Gopalkrishna text book.