UNIT III: THERMAL PHYSICS

Transfer of heat energy – thermal expansion of solids and liquids – expansion joints - bimetallic strips - thermal conduction, convection and radiation – heat conductions in solids – thermal conductivity - Forbe's and Lee's disc method: theory and experiment - conduction through compound media (series and parallel) – thermal insulation – applications: heat exchangers, refrigerators, ovens and solar water heaters.

Thermal conductivity

Thermal conductivity (K) is the intrinsic property of a material which relates its ability to conduct heat. Also, it is the relative ease or difficulty of the transfer of energy through the material. It depends on the bonding and structure of the material. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates to higher molecular energy or more molecular movement. Energy is transferred from the more energetic to the less energetic molecules when neighbouring molecules collide.

Thermal conductivity is defined as the quantity of heat (Q) transmitted through a unit thickness (L) in a direction normal to a surface of unit area (A) due to a unit temperature gradient (ΔT) under steady state conditions and when the heat transfer is dependent only on the temperature gradient. In equation form this becomes

Thermal Conductivity = heat × distance / (area × temperature gradient) = $K = \dfrac{QL}{A\Delta T}$

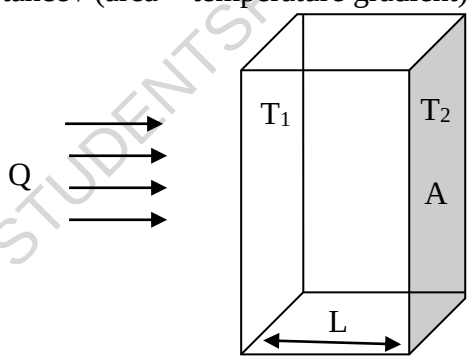


Figure 1: Thermal Conductivity

STUDENTSFOCUS.COM

Thermal expansion of Solids, Liquids and Gases

Thermal expansion is the tendency of matter to change in shape, area, and volume in response to a change in temperature. Temperature is a monotonic function of the average molecular kinetic energy of a substance. When a substance is heated, the kinetic energy of its molecules increases.

Definition: Increase in linear dimensions of a solid or in volume of a fluid because of rise in temperature.

Basic properties of thermal expansion

First, thermal expansion is clearly related to temperature change. The greater the temperature change, the more a bimetallic strip will bend. Second, it depends on the material. In a thermometer, for example, the expansion of alcohol is much greater than the expansion of the glass containing it.

Thermal expansion occurs in solids, liquids and gases. The atoms themselves do not expand, but the volume they take up does. When a solid is heated, its atoms vibrate faster about their fixed points.

I. Liquids

Liquids can only expand in volume. $\Delta V = \beta V_0 \Delta T$

Liquids have higher expansivities than solids. $\beta \sim 10^{-3}$/K, $3\alpha \sim 10^{-5}$/K

Applications

Liquid in glass thermometer. The alcohol is colored red to look like wine.

ethyl alcohol: 1120×10^{-6}/K

mercury: 181×10^{-6}/K

II. Solids

For many solids, expansion is directly proportional to temperature change.

$$\Delta \ell = \alpha \ell_0 \Delta T$$

Areas expand twice as much as lengths do.

$$\Delta A = 2\alpha A_0 \Delta T$$

Volumes expand three times as much as lengths do.

$$\Delta V = 3\alpha V_0 \Delta T$$

Applications

- buckling
- expansion gap/joint
- anti-scalding valve
- bimetallic strip, thermostat
- expansion of holes (mounting train tires)

Measurement techniques

- length comparator
- push rod dilatometer (gives relative expansion, since the device itself expands)
- interferometer (highest precision method)
- x-ray diffractometer
- capacitance dilatometer
- strain gauge
- optical dilatometer (basically a digital camera)

Anisotropic expansion

- Some materials expand differently in different directions, notably graphite and wood (lumber).

III. Gases

Behavior of gases is more complicated, gases will expand as much as pressure will allow.

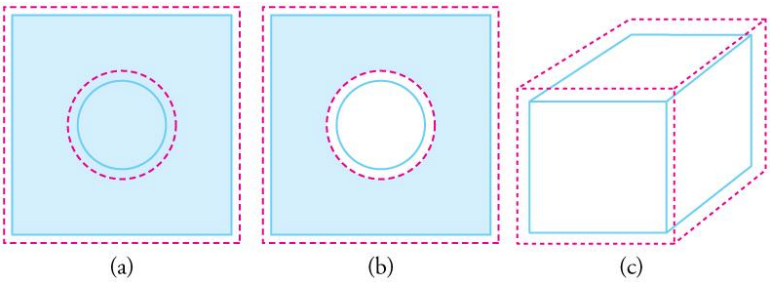


Figure 2: Expansion in Gases

STUDENTSFOCUS.COM

In general, objects expand in all directions as temperature increases. In these drawings, the original boundaries of the objects are shown with solid lines, and the expanded boundaries with dashed lines. (a) Area increases because both length and width increase. The area of a circular plug also increases. (b) If the plug is removed, the hole it leaves becomes larger with increasing temperature, just as if the expanding plug were still in place. (c) Volume also increases, because all three dimensions increase.

I. Thermal Expansion in One Dimension (Linear Thermal Expansion)

The change in length ΔL is proportional to length L. The dependence of thermal expansion on temperature, substance, and length is summarized in the equation $\Delta L=\alpha L\Delta T$, where ΔL is the change in length L, ΔT is the change in temperature, and α is the **coefficient of linear expansion**, which varies slightly with temperature.

II. Thermal Expansion in Two Dimensions (Superficial Thermal Expansion)

For small temperature changes, the change in area ΔA is given by $\Delta A=2\alpha A\Delta T$ where ΔA is the change in area A, ΔT is the change in temperature, and α is the coefficient of linear expansion, which varies slightly with temperature.

III. Thermal Expansion in Three Dimensions (Volume Expansion)

The change in volume ΔV is very nearly $\Delta V=3\alpha V\Delta T$. This equation is usually written as $\Delta V=\beta V\Delta T$, where β is the **coefficient of volume expansion** and $\beta\approx3\alpha\beta\approx3\alpha$. The values of β are almost exactly equal to 3α

STUDENTSFOCUS.COM

Thermal Stress

Thermal stress is created by thermal expansion or contraction. Thermal stress can be destructive e.g. when expanding gasoline ruptures a tank. Thermal stress can also be useful, e.g., when two parts are joined together by heating one in manufacturing, then slipping it over the other and allowing the combination to cool. Other examples are, the weathering of rocks and pavement by the expansion of ice when it freezes.

Expansion Joint

Flexible piping parts that are stable enough to avoid buckling.

Application of expansion joints

- Temperature elongation: Avoiding pipe stress
- Ground movement: Avoiding pipe damage
- Vibrations: Protect pipes and equipment. Reduce sound level.

Advantages of using expansion joints:

- Less pipe and space needed. (Less supports)
- Stress can be reduced, relieving the pipe and connected equipment.
- In case of malfunctioning or operational errors the expansion joint probably will be damaged, saving more expensive equipment.

Bimetallic strip

A bimetallic strip consists of two metals with different coefficients of thermal expansion, will bend or straighten, based on the temperature. Bimetallic strips have been used in iron boxes, electric kettles, and refrigerators. A schematic showing the functioning of the bimetallic strip is shown in Figure 3.

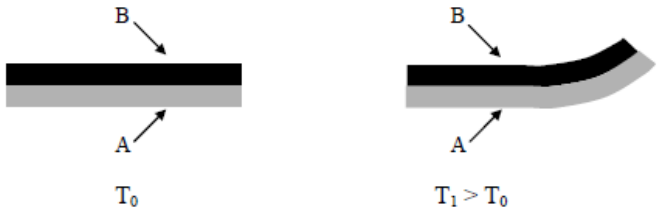


Figure 3: Schematic of a bimetallic strip, made of metals A and B

A bimetallic strip is made of two ribbons of dissimilar metals bonded together. At a lower temperature T_0, the two metals have the same length. At a higher temperature T_1, metal A has expanded more than metal B, and this results in the strip bending to accommodate the different lengths.

Assume that the strip is originally straight. As they are heated, the metal with the greater average coefficient of expansion (α_2) expands more than the other, forcing the strip into an arc, with the outer radius having a greater circumference (as in the Figure 3).

Application

Electrical breakers use bimetallic strips. When excessive current passes through the strip, it heats up and bends to trip the switch to interrupt the current. A typical circuit breaker handles a single circuit (~ 20 A). Thus, a 20 A current will heat the bimetallic strip, bend it down and release the spring-loaded trip lever. Another mechanism handles large surges from a short circuit. A small electromagnet will pull the bimetallic strip down instantly in case of a large current surge.

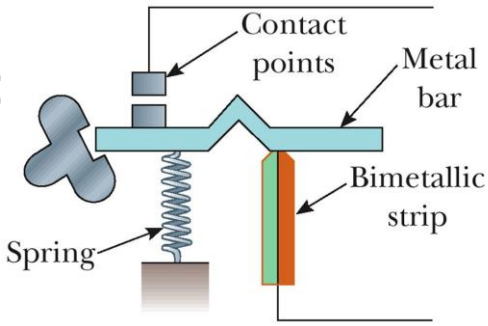


Figure 4: Electrical breaker

Thermal Insulators

Materials that prevent or reduce various modes of heat transfer (conduction, convection and radiation) from the outside to the inside or vice versa, whether the environment temperature is high or low. The sole purpose of thermal insulation is to reduce heat transfer by conduction, convection and radiation.

Thermal Properties of Insulator

A lesser value of the coefficient of thermal conductivity, indicates better resistance to heat transfer. The other thermal properties are: high reflectivity, low absorptivity, heat capacity, low density, high coefficient of thermal expansion and the low coefficient of thermal bridging.

Classification of Thermal Insulators

I. According to the material

1. Organic materials, such as cotton, wool, cork, rubber and cellulose. 2. Inorganic materials: such as glass, asbestos, rockwool, perlite, vermiculite and calcium silicate. 3. Metals: such as aluminum foils and tin reflectors.

II. According to the Shape

Rolls: vary in the degree of flexibility and the ability to bend or pressure. They could be fastened by nails like glass wool, rock wool, polyethylene and foil-ceramic rolls. Sheets: There are specific dimensions and thicknesses such as polyethylene layers, polystyrene, cork and cellulose. Liquid or gaseous fluids: poured or sprayed on to form the desired dielectric layer, such as polyurethane foam and epoxy. Grains: a powder or granules are usually placed in the spaces between the walls and it can also be mixed with some other materials. Examples of such materials granulated cork and polymers.

III. According to Functionality

a. House thermal insulation: Insulation in the walls, ceilings and floors reduces the loss of heat from the warm interior to the cold exterior during winter and reduces the entry of heat from the warm exterior to the cool interior during summer.
b. Industrial thermal insulation: This encloses the heating equipment, pipes that carry steam and cold storage spaces. Fuel or power is conserved and thermal equilibrium is maintained in the enclosure.
c. Building thermal insulation:

STUDENTSFOCUS.COM

Common insulators

Air is one of the best thermal insulators due to its low coefficient of thermal conductivity ($\approx$ 0.025 W/mK) and availability everywhere.

1. Cellulose: which is made from wood or recycled paper and is characterized by its susceptibility to water and dust absorption. 2. Corkboard: This is taken from cork tree. 3. Glass wool: are widely used to insulate buildings, as well as boilers and reservoirs. 4. Rock wool: This material is used to isolate the buildings and storages. 5. Polyurethane: usually uses as insulated panel or foam to fill the cracks. 6. Polystyrene cork: both types, EPS and XPS. It could be made from industrial petroleum product which is called the Expanded Polystyrene (EPS). It is found in the form of panels and used as thermal and acoustic insulators. 7. Astrofoil (XPE) layers 8. Polycarbonate panels 9. Reflective materials 10. Fire retardant sheets

Advantages of Thermal Insulation

1. Reduce the amount of heat transmitted through the parts of the house. 2. Reduce the energy required for heating or cooling the house. 3. Make the internal temperature of the building stable, non-volatile. 4. Keep the temperature of the building elements stable thus long lifetime. 5. Reduce energy bills. 6. Reduce the burning of fuel in power plants. 7. Reduce the emission of greenhouse gases.

Heat Exchangers

Introduction

Some widely used heat transfer devices are heat exchangers. Heat exchangers are thermal devices that transfer or exchange heat from one fluid stream to one or more others. It is a broad description to a vast range of hardware that operates in one of three ways:

1. by recuperation, or recovery, or direct transfer of heat from a hot stream to a cold stream;

2. by regeneration, or indirect transfer of the hot and cold streams alternatively through a matrix;
3. by direct contact of one fluid stream with another.

Some examples are,

Recuperation: Automotive radiators, oil coolers, power station condensers, economizer. Regenerative: Rotating matrix used to preheat exhaust gases, Stirling Cycle engine

Direct contact: Cooling of hot metal sheet by a spray of water or air jet, cooling tower.

In recuperative heat exchangers, mixing and contamination is prevented by solid walls. The dominant mechanisms of heat transfer are illustrated in Figure 5.

Convection: A to wall
Conduction: Through wall
Convection: wall to B

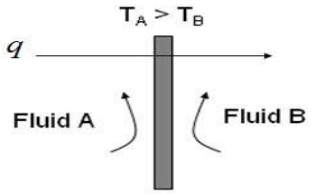


Figure 5: Mechanism of heat transfer in a heat exchanger

There are at least two main objectives to the analysis of heat exchangers. The first is the design of a heat exchanger to fulfil a certain duty, providing geometric parameters. The second is the prediction of performance of a particular design working out inlet and outlet temperatures and heat flux.

STUDENTSFOCUS.COM

Classification of Heat Exchangers

Heat Exchangers are classified either by flow arrangement, by construction or by their degree of compactness.

I. Classification by flow arrangement

Heat exchangers can be parallel flow, counter flow or cross flow as shown in Figure. In parallel flow heat exchangers, both flows run side by side, for example in concentric pipes. Counter flow heat exchangers are similar except the cold and hot streams go in opposite directions. Cross flow heat exchangers have the two-flow stream normal to one another.

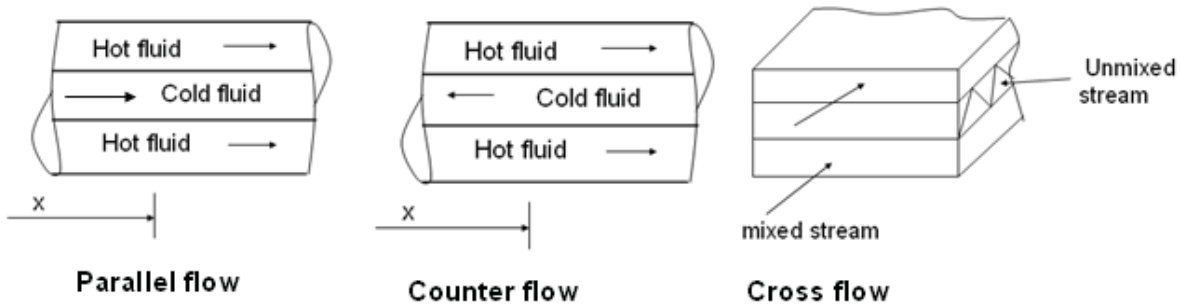


Figure 6: Classification of heat exchangers by flow arrangement

The exit temperature of the cold stream cannot by higher than the exit temperature of the hot stream for the parallel flow heat exchangers, while this is possible for counter flow heat exchangers.

A typical example of cross flow heat exchangers is the plate-Plate-and-fin heat exchanger. In these types, flow channels are constructed from parallel plates separated by fins. Fins are used in both sides in gas to gas applications and on the gas side for gas to liquid applications such as automotive radiators. These can be either mixed or unmixed flow heat exchangers depending on whether the flow across the tubes is separated into various channels by plates or not. Typical cross flow heat exchangers are shown in Figure 7.

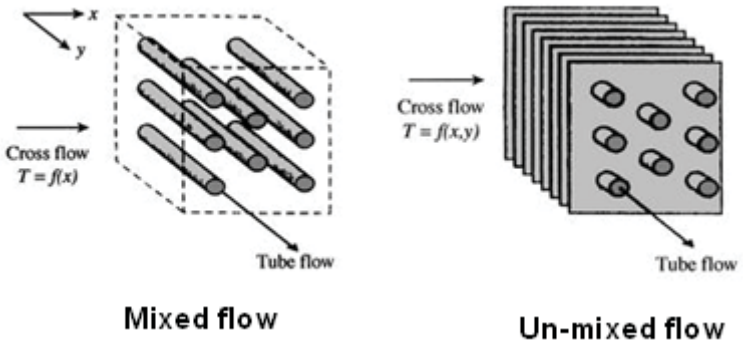
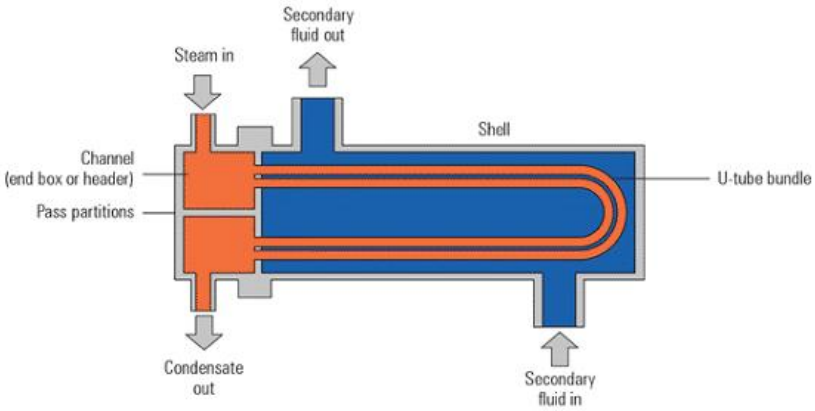


Figure 7: Examples of cross flow heat exchangers

II. Classification by construction

A double pipe heat exchanger has a relatively poor performance resulting in a very large physical size to perform a given duty consequently; they are rarely used in practical applications in this form. In practice, other arrangements are possible which allow reduction in the physical size of the heat exchanger. Examples are the U-tube bundle and the shell and tube heat exchangers shown in Figure 8.



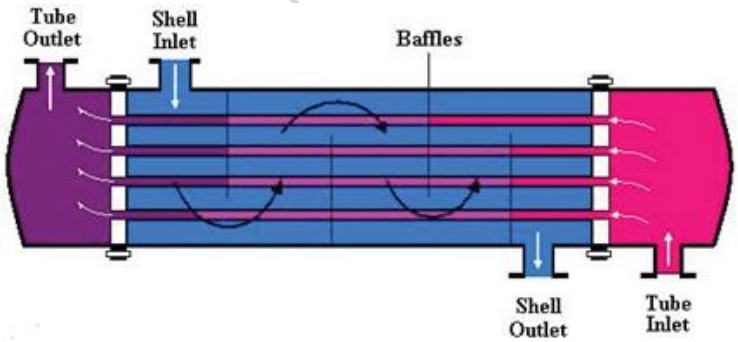
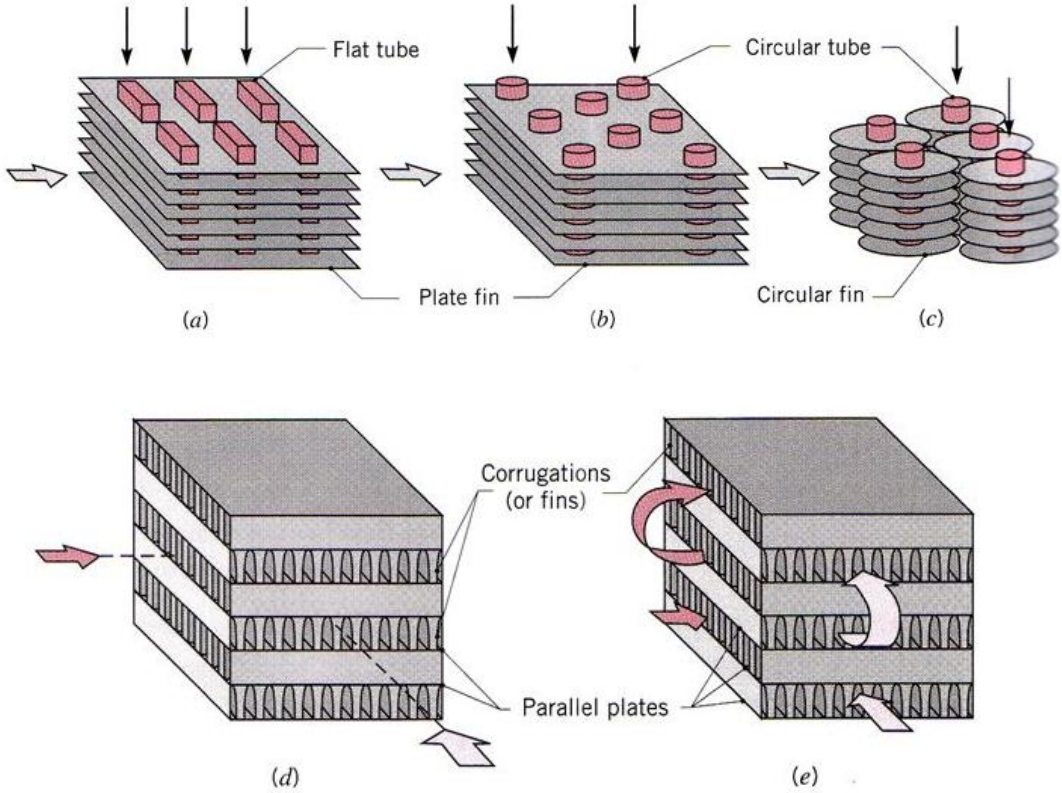


Figure 8: U-tube and shell-and-tube heat exchangers

A shell and tube is a development of a double pipe heat exchanger. This is a common form of construction, cheap and robust. However, it is very heavy. Internal baffles are used to force the outer stream to cross the tubes, improving convective heat transfer.

III. Classification by compactness

Another way of classifying heat exchangers is the degree of compactness. This is expressed as the ratio the surface area to volume. Compact heat exchangers are devices offering high surface area to volume ratio. This can be achieved in a number of ways. They tend to be used in gaseous, rather than liquid where the heat transfer coefficients are low. Examples of compact heat exchangers are shown in Figure 9.



Compact heat exchanger cores. (*a*) Fin–tube (flat tubes, continuous plate fins). (*b*) Fin–tube (circular tubes, continuous plate fins). (*c*) Fin–tube (circular tubes, circular fins). (*d*) Plate–fin (single pass). (*e*) Plate–fin (multipass).

Figure 9: Examples of compact heat exchangers

Refrigerator

A refrigerator can be thought of as a heat engine in reverse.

Principle

The cooling effect in a refrigerator is achieved by a cycle of condensation and vaporization of the nontoxic compound CCl_2F_2 (Freon-12). The passage of the cool refrigerant gas absorbs the heat from the items inside the refrigerator and loses the heat to the relatively cooler surrounding outside.

Construction

As shown in Figure 10, the refrigerator contains (1) an electrically-powered compressor that does work on Freon gas, and (2) a series of coils that allow heat to be released outside (on the back of) the refrigerator or absorbed from inside the refrigerator as Freon passes through these coils.

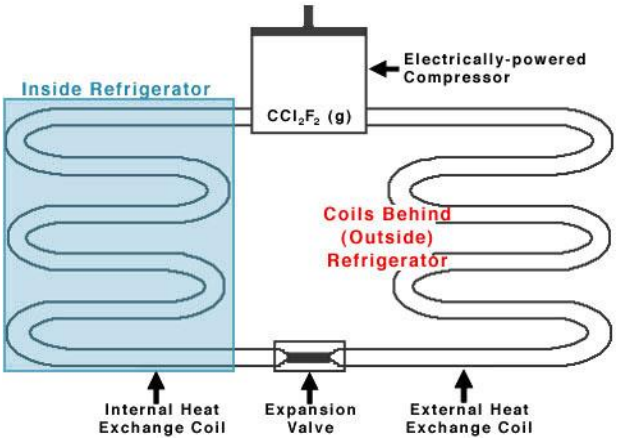


Figure 10: Schematic diagram of the major functional components of a refrigerator.

The phase transitions of Freon and their associated heat-exchange events that occur during the refrigeration cycle are given as the steps of the refrigeration cycle are described in the figure 11 below.

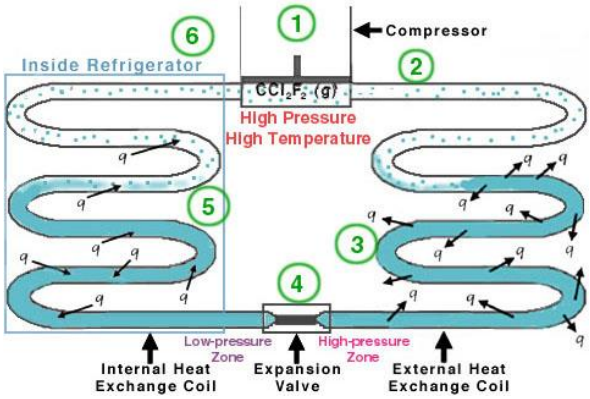


Figure 11: Major steps in the refrigeration cycle

1. Outside of the refrigerator, the electrically-run compressor does work on the Freon gas, increasing the pressure of the gas. As the pressure of the gas increases, so does its temperature (as predicted by the ideal-gas law).
2. Next, this high-pressure, high-temperature gas enters the coil on the outside of the refrigerator.
3. Heat (q) flows from the high-temperature gas to the lower-temperature air of the room surrounding the coil. This heat loss causes the high-pressure gas to condense to liquid, as motion of the Freon molecules decreases and intermolecular attractions are formed. Hence, the work done on the gas by the compressor (causing an exothermic phase transition in the gas) is converted to heat given off in the air in the room behind the refrigerator.
4. Next, the liquid Freon in the external coil passes through an expansion valve into a coil inside the insulated compartment of the refrigerator. Now, the liquid is at a low pressure (as a result of the expansion) and is lower in temperature (cooler) than the surrounding air (*i.e.*, the air inside the refrigerator).
5. Since heat is transferred from areas of greater temperature to areas of lower temperature, heat is absorbed (from inside the refrigerator) by the liquid Freon, causing the temperature inside the refrigerator to be reduced. The absorbed heat begins to break the intermolecular attractions of the liquid Freon, allowing the endothermic vaporization process to occur.
6. When all of the Freon changes to gas, the cycle can start over.

STUDENTSFOCUS.COM

The cycle described above does not run continuously, but rather is controlled by a thermostat. When the temperature inside the refrigerator rises above the set temperature, the thermostat starts the compressor. Once the refrigerator has been cooled below the set temperature, the compressor is turned off. This control mechanism allows the refrigerator to conserve electricity by only running as much as is necessary to keep the refrigerator at the desired temperature.

Oven

PRINCIPLE

Fine gravity air convection in an electrically heated chamber of the oven. The forced circulation of hot air inside the oven chamber by rapidly circulating it back to bottom by a fan installed inside the chamber ensures that optimum amount of heat is achieved gradually inside all the corners of the oven.

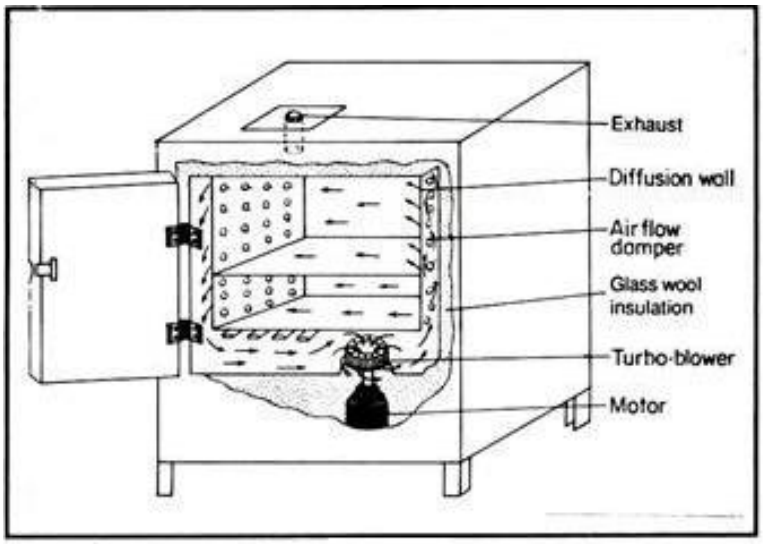


Figure 12: Oven

CONSTRUCTION

The apparatus consists of a large, rectangular, copper-base chamber and covered with asbestos sheets. It is also provided with a door and erected on a four-legged stand. The double walled chamber of hot air ovens is filled with high grade insulation to prevent heat loss. The door of hot air oven closes on to an asbestos gasket. The shelves slide neatly into the fixed runners. Insulation materials such as glass fibres of asbestos is filled between the two walls of the oven to avoid heat loss. The door is also double walled having asbestos gasket on its inner side. There is also an air-filled space in between to aid insulation. These are fitted with the adjustable wire mesh plated trays or aluminium trays and consist of fan for distribution of air uniformly. Two or three perforated shelves are fixed inside the oven to place the materials for sterilization. The oven is heated by electrically operated heater, fitted at the base of the instrument. There is a regulator of heater to control the inside temperature. An electrical fan is also fitted to ensure the uniform circulation of hot air in the oven in order to maintain the required temperature in all the shelves. Heating elements are fitted on the bottom of the oven and it is thermostatically controlled. A thermometer is fitted in the oven to note down the temperature inside the oven.

WORKING

The working of the hot air oven is based on the forced circulation of hot air inside the chamber of oven by the convection. As it is a universal scientific fact that in any chamber hot air rises above. Thus, by utilizing this principle when the hot air reaches the top of chamber it is circulated back to bottom by a fan installed inside the chamber and hence optimum amount of heat is achieved gradually inside the hot air oven.

Before sterilisation, the glassware are dried properly and wrapped in brown paper and then exposed to hot air inside the oven. After loading of glassware, the oven is switched on to 160°C. The temperature will increase slowly up to the desired point where it will remain steady. Then at 160°C the oven is kept for an hour. This is the appropriate temperature for sterilisation of glassware. After heating the content of the oven for two hours at 160 °C, the articles are allowed to remain there, till the temperature comes down to 40 °C. Then gradually the temperature is brought down and thereafter sterilisation is complete then the sterilized materials are removed from the oven.

ADVANTAGES

1. Sterilisation of those substances which gets spoiled during moist heat sterilisation. Eg: oily materials and powders.
2. Sterilisation of assembled equipment such as all glass syringes due to expose to high temperature for a long time.
3. Does not damage glass and metals equipment as moist heat.
4. Dry heat will not corrode or rust instruments or needles.

5. Dry heat will sterilize instruments containing many parts that cannot be disassembled

DISADVANTAGES

1. Unsuitable for surgical dressings, medicaments, rubber and plastic good because the articles are exposed to a very high temperature for a long period.
2. Dry heat penetrates slowly and unevenly and requires long exposure times to effectively achieve sterility.
3. Dry heat requires higher temperatures that many items cannot be safely exposed to.
4. Dry heat requires specialized packaging materials that can sustain integrity under high heat conditions.
5. Dry heat may require different temperature and exposure times, depending on the type of item being sterilized.

Solar Water Heater

A solar thermal device captures and transfers the heat energy available in solar radiation which can be used for meeting the requirements of heat in different temperature ranges.

Three main temperature ranges used are -

Low temperature - Hot water - 60°C to 80°C

Medium temperature - Drying - 80°C to 140°C

High temperature - Cooking & power generation - > 140°C

STUDENTSFOCUS.COM

Configuration

Solar water heating system (SWHS) is a device which supplies hot water at 60°C to 80°C using only solar thermal energy without any other fuel. It has three main components, namely,

1. Solar Collector 2. Insulated hot water storage tank and 3. Cold water tank with required insulated hot water pipelines and accessories.

Working Principle

In a typical solar water heater, water is heated by the solar thermal energy absorbed by the collectors. The hot water with lower density moves upwards and cold water with higher density moves down from the tank due to gravity head. A bank of collectors can be arranged in a series – parallel combination to get higher quantity of hot water. Based on the collector system, solar water heaters can be of two types.

I. Flat Plate Collectors (FPC) based Solar Water Heaters

Flat Plate Collector is a heat exchanger that converts the radiant solar energy from the sun into heat energy using the well-known greenhouse effect. For most residential and small commercial hot water applications, the *solar flat plate collector* tends to be more cost effective due to their simple design, low cost, and relatively easier installation compared to other forms of hot water heating systems. Also, solar flat plate collectors are more than capable of delivering the necessary quantity of hot water at the required temperature.

A solar flat plate collector typically consists of a large heat absorbing plate, usually a large sheet of copper or aluminium as they are both good conductors of heat, which is painted or chemically etched black to absorb as much solar radiation as possible for maximum efficiency. This blackened heat absorbing

surface has several parallel copper pipes or tubes called risers, running length ways across the plate which contain the heat transfer fluid, typically water.

These copper pipes are bonded, soldered or brazed directly to the absorber plate to ensure maximum surface contact and heat transfer. Sunlight heats the absorbing surface which increases in temperature. As the plate gets hotter this heat is conducted through the risers and absorbed by the fluid flowing inside the copper pipes which is then used by the household.

The pipes and absorber plate are enclosed in an insulated metal or wooden box with a sheet of glazing material, either glass or plastic on the front to protect the enclosed absorber plate and create an insulating air space. This glazing material does not absorb the suns thermal energy to any significant extent and therefore most of the incoming radiation is received by the blackened absorber.

The air gap between the plate and glazing material traps this heat preventing it from escaping back into the atmosphere. As the absorber plate warms up, it transfers heat to the fluid within the collector but it also loses heat to its surroundings. To minimize this loss of heat, the bottom and sides of a flat plate collector are insulated with high temperature rigid foam or aluminium foil insulation as shown in Figure 13.

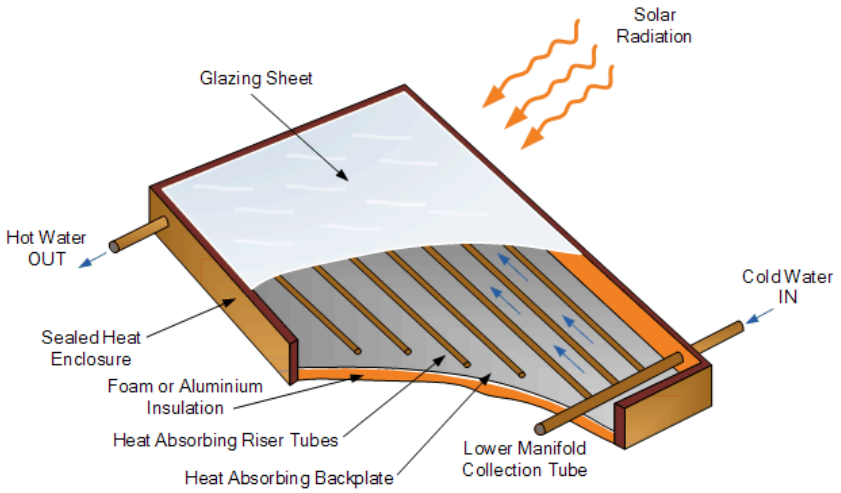


Figure 13: Flat Plate Collectors (FPC) based Solar Water Heaters

Flat plate collectors can heat the fluid inside using either direct or indirect sunlight from a wide range of different angles. They also function in diffused light, which is dominant on cloudy days as it is the surrounding heat that is being absorbed and not the light, unlike photovoltaic cells. How hot the circulating water gets will depend mostly on the time of the year, how clear the skies are and how slowly the water flows through the collectors pipes.

II. Evacuated Tube Collectors (ETC) based Solar Water Heaters

The **Evacuated tube collector** consists of a number of rows of parallel transparent glass tubes connected to a header pipe and which are used in place of the blackened heat absorbing plate we saw in the previous flat plate collector. These glass tubes are cylindrical in shape. Therefore, the angle of the sunlight is always perpendicular to the heat absorbing tubes which enables these collectors to perform well even when sunlight is low such as when it is early in the morning or late in the afternoon, or when shaded by clouds. Evacuated tube collectors are particularly useful in areas with cold, cloudy wintry weather. Evacuated tube collectors are made up of a single or multiple row of parallel, transparent glass tubes supported on a frame. Each individual tube varies in diameter from between 1" (25mm) to 3" (75mm) and between 5′ (1500mm) to 8′ (2400mm) in length depending upon the manufacturer. Each tube consists of a thick glass outer tube and a

thinner glass inner tube, (called a “twin-glass tube”) or a “thermos-flask tube” which is covered with a special coating that absorbs solar energy but inhibits heat loss. The tubes are made of borosilicate or soda lime glass, which is strong, resistant to high temperatures and has a high transmittance for solar irradiation.

Unlike flat panel collectors, evacuated tube collectors do not heat the water directly within the tubes. Instead, air is removed or evacuated from the space between the two tubes, forming a vacuum (hence the name **evacuated tubes**). This vacuum acts as an insulator reducing any heat loss significantly to the surrounding atmosphere either through convection or radiation making the collector much more efficient than the internal insulating that flat plate collectors have to offer. With the assistance of this vacuum, evacuated tube collectors generally produce higher fluid temperatures than they’re flat plate counterparts so may become very hot in summer.

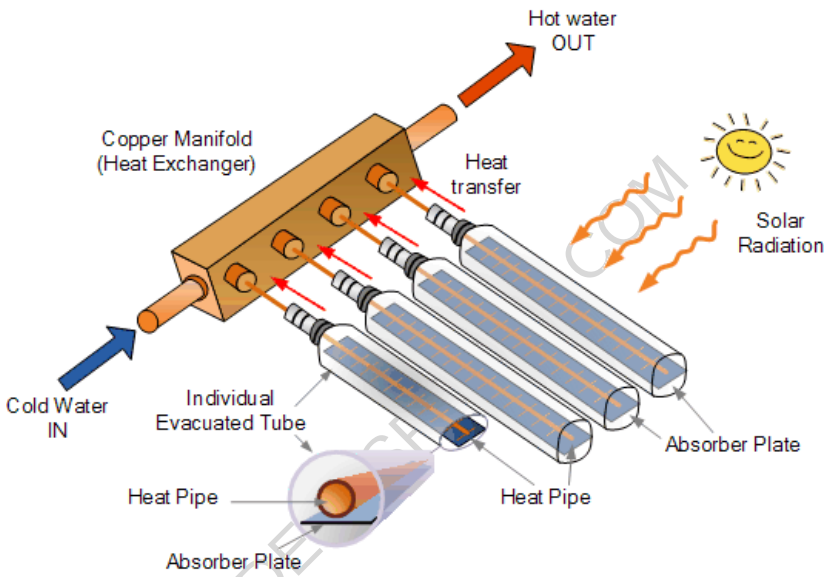


Figure 14: Evacuated Tube Collectors (ETC) based Solar Water Heaters

Selection of suitable Solar Water Heating Systems:

1. Flat plate collector (FPC) based systems are of metallic type and have longer life as compared to Evacuated tube collector (ETC) based system as ETCs are made of glass which are of fragile in nature. 2. ETC based systems are 10 to 20% cheaper than FPC based system. They perform better in colder regions and avoid freezing problem during sub-zero temperature. FPC based systems also perform good with anti-freeze solution at sub zero temperature but their cost increases. 3. At places where water is hard and have larger chlorine content, FPC based system with heat exchanger must be installed as it will avoid scale deposition in copper tubes of solar collectors which can block the flow of water as well reduce its thermal performance. ETC based systems do not face such problem.