# UNIT 1 REFRIGERATION AND AIR CONDITIONING

## Structure


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## 1.1 INTRODUCTION

For specific applications, efficiencies of both living and non-living beings depend to a great extent on the physical environment. The nature keeps conditions in the physical environment in the dynamic state ranging from one extreme to the other. Temperature, humidity, pressure and air motion are some of the important environment variables that at any location keep changing throughout the year. Adaptation to these many a times unpredictable variations is not possible and thus working efficiently is not feasible either for the living beings or the non-living ones. Thus for any specific purpose, control of the environment is essential. Refrigeration and air-conditioning is the subject which deals with the techniques to control the environments of the living and non-living subjects and thus provide them comforts to enable them to perform better and have longer lives.

### Objectives

After studying this unit, you should be able to

- know what is refrigeration and air-conditioning,
- know the history of refrigeration,
- know applications of refrigeration and air-conditioning, and
- describe the term ton of refrigeration and COP.

## 1.2 DEFINITIONS

**Refrigeration**

Literal meaning of refrigeration is the production of cold confinement relative to its surroundings. In this, temperature of the space under consideration is maintained at a temperature lower than the surrounding atmosphere. To achieve this, the mechanical device extracts heat from the space that has to be maintained at a lower temperature and rejects it to the surrounding atmosphere that is at a relatively higher temperature. Since the volume of the space which has to be maintained at a lower temperature is always much lower than the environment, the space under consideration experiences relatively higher change in temperature than the environment where it is rejected.

The precise meaning of the refrigeration is thus the following: Refrigeration is a process of removal of heat from a space where it is unwanted and transferring the same to the surrounding environment where it makes little or no difference. To understand the above definition, let us consider two examples from the daily life.

It is a well-known fact that the spoilage of food and many other items reduces at a lower temperature. At a lower temperature, molecular motion slows down and the growth of bacteria that causes food spoilage also retards. Thus to preserve many types of perishable food products for a longer duration, we use refrigerators (Figure 1.1) in our homes, canteens, hotels, etc. The temperature of the food products has to maintained at a level below that of surroundings. For this we keep the food products in a refrigerator. The inside volume of the refrigerator where we store food products or any other items is much less than the volume of the room where the refrigerator is kept. The room in this case is the surrounding environment. Food products in the refrigerator initially were at a higher temperature than desired temperature, meaning that it had some unwanted heat. If its heat is removed, its temperature will decrease. The refrigerator removes unwanted heat from the food products and throws away that heat to the room – the surrounding environment of the refrigerator. The amount of heat makes a big difference in temperature inside the refrigerator and almost little or no difference in the temperature of the room.

**Figure 1.1 : Spoilage of Food Products in a Refrigerator Slows Down. Temperature in the Refrigerated Space is Lower than the Room where Refrigerator is Kept. Refrigerator Throws Away Heat from the Food Products to the Room**

As a second example let us consider travel in a car in an Indian summer of Delhi or Kanpur. Outside temperature is very high. It is highly uncomfortable. For a comfortable drive, now-a-days we have air-conditioned cars. You will come to know later, that refrigeration is an integral component of air-conditioning. To have a comfortable drive in the car, the temperature inside the car has to be lowered from about 40$^{o}$C to 25 $^{o}$C. This means that heat of the space inside of the car and its occupants has to be thrown outside. This is done by the refrigeration unit fitted in the car. The volume of the car is much less than that of the surroundings. With the rejected heat there is an appreciable change in the temperature inside the car, but no change in the temperature of the surroundings.

In many places and situations, environment temperature is lower than the temperature of the space that we desire. As an example consider car driving in the Winter of Delhi or Kanpur. Temperature outside is about 2-6$^{o}$C. For a comfortable drive with light clothing, temperature inside the car has to be about 25$^{o}$C. This means that heat has to be supplied or pumped inside the car and thus its temperature has to be increased. The machinery that performs this operation is known as heat pump. But in applications such as that of the comfortable driving in a car that depending upon the season requires temperature to be lower or higher than the surroundings, heat has to be pumped to the car or rejected from the car. Since both the operations are performed by the same unit in the car, in a much broader sense we can say that a refrigeration unit controls the temperature of a space. In the normal refrigeration system, this is done by reversing the operation.

That is a refrigeration system can also be used as a heat pump.

**Figure 1.2 : Journey in a Car is Comfortable if the Temperature Inside the Car is Maintained at about 25 °C. To do so, in a Summer, Heat from inside the Car has to be Rejected to the Surroundings**

In refrigeration, heat is pumped out from a lower temperature space to a higher temperature environment. We know from our experience in daily life that water flows from a higher level to a lower level and heat flows from a body at a higher temperature to a body at a lower temperature. The reverse, i.e., flow of water from a lower level to a higher level and flow of heat from a body at a lower temperature to a body at a higher temperature do not occur naturally. In practice these are achieved at the cost of external work (power) done on the water and the carrier of heat (here the refrigerant) with help of a mechanical device.

Whether the space under consideration has to be maintained at a temperature lower or higher than the surrounding environment, to pump out or in the heat, external power is always required. In relation to heat pump, this will be explained later.

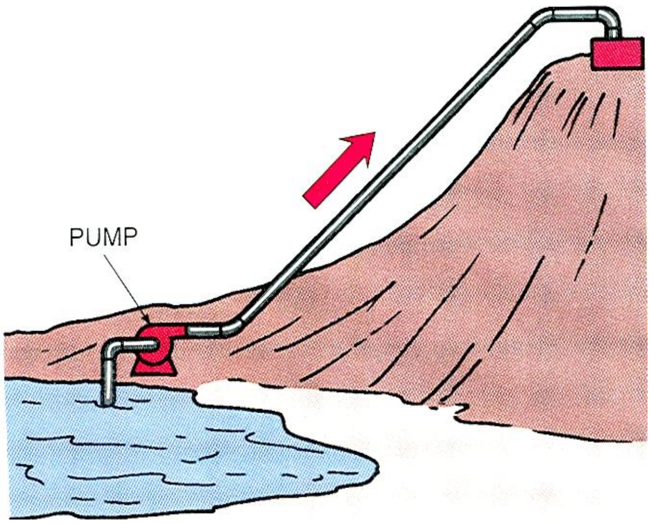


**Figure 1.3 : Power is required to Pump Water uphill; the Same is true for Pumping Heat from a Lower Temperature Body to a Higher Temperature Body**

## Air Conditioning

Merely lowering or raising the temperature does not provide comfort in general to the machines or its components and living beings in particular. In case of the machine components, along with temperature, humidity (moisture content in the air) also has to be controlled and for the comfort of human beings along with these two important parameters, air motion and cleanliness also play a vital role. Air conditioning, therefore, is a broader aspect which looks into the simultaneous control all mechanical parameters which are essential for the comfort of human beings or animals or for the proper performance of some industrial or scientific process. The precise meaning of air conditioning can be given as the process of simultaneous control of temperature, humidity, cleanliness and air motion. In some applications, even the control of air pressure falls under the purview of air conditioning. It is to be noted that refrigeration that is control of temperature is the most important aspect of air conditioning.

To understand the above definition in a better way, let us consider one example. In the summer, the temperature in Delhi is about 10 $^oC$ higher than in Kolkata where temperature varies in the range of 32 $^oC$ to 35 $^oC$. We feel uncomfortable in both places. Weather in Delhi is hot and dry (moisture content in the air is low) whereas in Kolkata it is (mild) hot but humid (moisture content in the air is very high). If we go to a hill-station, say Shillong in the summer, we feel comfortable there. Temperature there remains about 25 $^oC$ and relative humidity of the air is also in the comfortable range, say about 65%. In Delhi, temperature is very high and humidity is low, whereas in Kolkota, temperature is low but humidity is high. In Delhi if there is a rain, we feel more comfortable whereas in Kolkata even with rain, the relative comfort is less. In Delhi temperature falls down and humidity also increases towards the comfortable value. In Koklata, temperature falls down but humidity still remains on the higher side. Thus, for comfort, both temperature and humidity have to be in the specified range. This is true for both human beings and scientific processes. Apart from the above two, from intuition one can also say that purity or cleanliness of the air is an essential item for the comfort and it has been established that the air motion is also required for the comfort condition.

Depending upon the requirement, air conditioning is divided into the summer air conditioning and the winter air conditioning. In the summer air conditioning, apart from cooling the space, in most of the cases, extra moisture from the space is removed, whereas in the winter air conditioning, space is heated and since in the cold places, normally the humidity remains low, moisture is added to the space to be conditioned. The summer air conditioning thus uses a refrigeration system and a dehumidifier. The winter air conditioning uses a heat pump (refrigeration system operated in the reverse direction) and a humidifier. Depending upon the comfort of the human beings and the control of environment for the industrial products and processes, air conditioning can also be classified as comfort air conditioning and industrial air conditioning. Comfort air conditioning deals with the air conditioning of residential buildings, offices spaces, cars, buses, trains, airplanes, etc. Industrial air conditioning includes air conditioning of the printing plants, textile plants, photographic products, computer rooms, etc.

It has been mentioned above that the refrigeration and air conditioning are related. Even when a space has to be heated, it can be done so by changing the direction of flow of the refrigerant in the refrigeration system, i.e., the refrigeration system can be used as a heat pump (how this is possible will be explained later). However, some section of the people, treat refrigeration exclusively the process that deals with the cooling of the space. They treat heating operation associated with the heat pump. The relationship between air conditioning and refrigeration fields can be understood from the Figure 1.4.

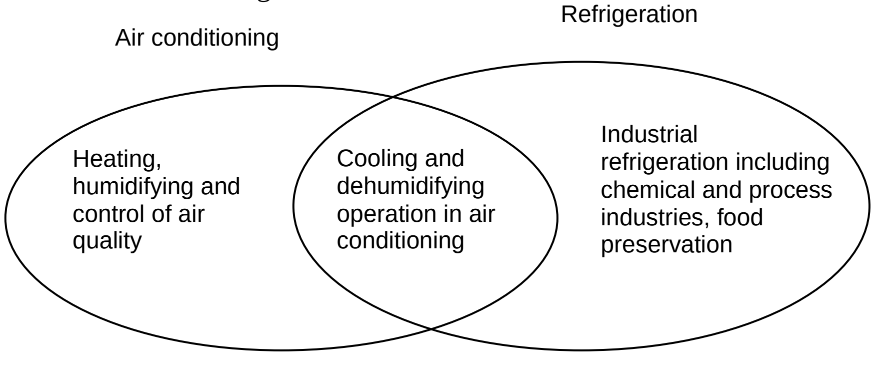


**Figure 1.4 : Relationship between the Refrigeration and Air Conditioning**

**SAQ 1**

(a) Explain the term refrigeration.

(b) Explain the term air conditioning.

(c) How is refrigeration different from air conditioning?

(d) How are refrigeration and air conditioning related?

(e) How is summer air conditioning different from the winter air conditioning?

## 1.3 BRIEF HISTORY OF REFRIGERATION

In the past around 4000 years from now, people in India and Egypt are known to produce ice by keeping water in the porous pots outside the home during the night period. The evaporation of water in almost cool dry air and radiative heat transfer between the water and the deep sky that is at a very low temperature (much below the freezing point of ice) caused the formation of ice even though the surrounding air was at a higher temperature than the freezing point of water. There are a few accounts in China about the use of ice around 1000 BC for cooling the beverages. In 4$^{th}$ century A.D., East Indians were producing ice by dissolving salt in water.

Because of the very small amount of production, the aforesaid methods were not feasible for commercial applications. Natural ice is limited to certain regions, therefore, the absence of good quality insulation systems in those days forced the man to develop methods to produce ice artificially. Out of many pioneers' work on refrigeration side, a few are presented here. In 1790 the first British Patent was obtained by Thomas Hariss and John Long. In 1834 Jacob Perkins developed a hand operated refrigeration system using ether as the working fluid (Figure 1.5). Ether vapor was sucked by the hand operated compressor and then high temperature and pressure ether vapor was condensed in the water cooled chamber that served as the condenser. Liquid ether was finally throttled to the lower pressure, which was then evaporated in a chamber called evaporator, A. With the evaporation, temperature of the water surrounding the evaporator fell down and finally the ice was formed. In this system, either was used again and again in the cyclic process with negligible wastage.

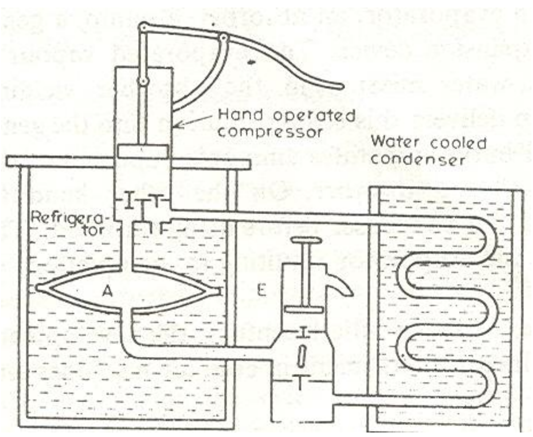


**Figure 1.5 : Schematic of the Hand-Operated Refrigeration Machine of Jacob Perkins**

The first American patent of a cold air machine to produce ice in order to cure people suffering from high fever was obtained by Dr. John Gorrie of Florida in 1851. In 1860, instead of air or ether, Dr. James Harrison of Australia used sulfuric ether. This was the world's first installation of refrigeration machine for brewery. In 1861, Dr. Alexander Kirk of England constructed a cold air machine similar to that of Dr. Gorrie. In his machine, air was compressed by a reciprocating compressor driven by a steam engine running on coal.

In the 19th century, there was remarkable development of refrigeration systems to replace natural ice by artificial ice producing machines. In the beginning of the 20th century, large sized refrigeration machines were developed. In 1904 in the New York Stock Exchange, about 450 ton cooling machine was installed. In Germany, people used air conditioning in theater. Around 1911 the compressors with speed between 100 to 300 rpm were developed. In 1915, the first two-stage modern compressor was developed.

To meet the demand for ice during the civil war, Ferdinand Carre of the USA developed a vapor-absorption refrigeration system (Figure 1.6) using ammonia and water. Carre's system consisted of an evaporator, an absorber, a pump, a generator, a condenser and an expansion device. The evaporated vapor is absorbed by the week ammonia-water mixture in the absorber yielding strong aqua ammonia. The pump delivers this strong solution into generator where heat transfer from a burner separates ammonia vapor and the weak ammonia returns to the absorber. On the other hand the ammonia vapor condenses in the condenser before being throttled. The throttled liquid ammonia enters the evaporator resulting in completion of the cyclic process.

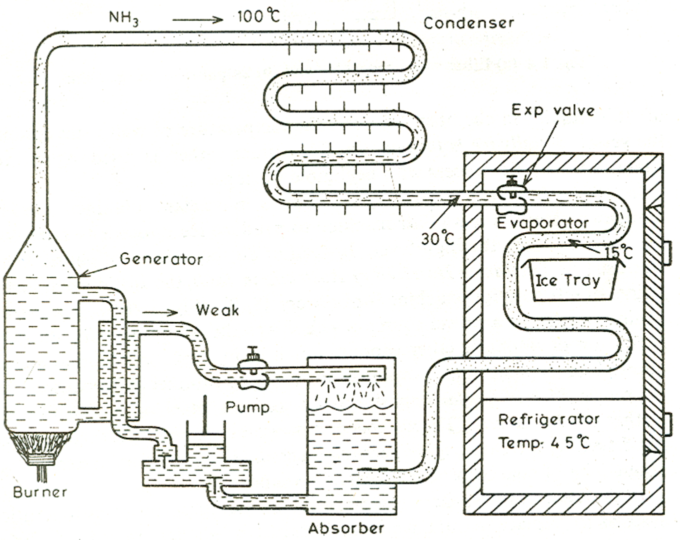


**Figure 1.6 : Vapor-Absorption Machine of Ferdinand Carre**

Until about 1920s the development in refrigeration system was restricted to the refinement in the cold-air machines and vapor-compression systems. After 1920s, there has been extensive diversification in the growth of refrigeration systems leading to new developments such as vortex tube, thermoelectric, pulse-tube, steam-jet, centrifugal compression systems, etc. The most important development can be the invention of new refrigerants which were chlorfluor hydrocarbons. This development occurred in 1930 in GE Corporation of USA at a time when Refrigeration industry had begun to stagnate on the use of $NH_3$ $SO_2$ as refrigerant. The chlorfluor carbons offered the advantages of best refrigerants and were proven non-toxic substances in comparison with $NH_3$ and $SO_2$ Other developments took place due to special requirements to utilize waste heat or low grade energy or materials of specific properties for thermoelectric effect. Owing to the likelihood of energy crisis in the future, many commercial units have been developed that utilizes waste heat or solar energy.

## SAQ 2

(a) Where is the first historical account of production of ice?

(b) Why natural way of the ice production was not suitable for commercial applications?

(c) Trace the development of the modern refrigeration systems.

## Applications of Refrigeration and Air Conditioning

The fields of refrigeration and air conditioning are although interconnected, as shown in Figure 1.4, each has its own province too. The largest application of refrigeration is for air conditioning. In addition, refrigeration embraces industrial refrigeration including the processing and preservation of food, removing heat from substances in chemical, petroleum and petrochemical plants, and numerous special applications such as those in the manufacturing and construction industries.

In a similar manner, air conditioning embraces more than cooling. The comfort air conditioning is the process of treating air to control simultaneously its temperature humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space. Air conditioning, therefore, includes entire heating operation as well as regulation of velocity, thermal radiation, and quality of air, including removal of foreign particles and vapors.

Some applications of refrigeration and air conditioning are as follows :

### Air Conditioning of Residential and Official Buildings

Most of the air conditioning units are devoted for comfort air conditioning that is meant to provide comfortable conditions for people. Air conditioning of building is required in all climates. In the summer, living/working spaces have to be cooled and in the winter the same have to be heated. Even in places where temperature remains normal, cooling of the building is required to remove the heat generated internally by people, lights, mechanical and electrical equipment. Further in these buildings, for the comfort, humidity and cleanliness of air has to be maintained. In hospitals and other medical buildings, conditions on cleanliness and humidity are more stringent. There ventilation requirements often specify the use of 100 percent outdoor air, and humidity limits.

### Industrial Air Conditioning

The term industrial air conditioning refers to providing at least a partial measure of comfort for workers in hostile environments and controlling air conditions so that they are favorable to processing some objects or materials. Some examples of industrial air conditioning are the following:

### Spot Heating

In a cold weather it may be more practical to warm a confined zone where a worker is located. One such approach is through the use of an infrared heater. When its surfaces are heated to a high temperature by means of a burner or by electricity, they radiate heat to the affected area.

**Figure 1.7 : An Infrared Heater is used to Heat a Confined Zone where a Worker is Located**

### Spot Cooling

If a specific area has to be cooled, it will be unwise to cool entire room or factory. In this case, conditions may be kept tolerable for workers by directing a stream of cool air onto occupied areas.

### Environmental Laboratories

The role of air conditioning may vary from one laboratory to the other. In one laboratory, a very low temperature, say – 40°C must be maintained to test certain equipment at low temperatures, and in another, a high temperature and humidity may be required to study behavior of animals in tropical climates.

### Printing

In printing industries, control of humidity is a must. In some printing processes the paper is run through several different passes, and air conditioning must be maintained to provide proper registration. If the humidity is not properly maintained the problems of static electricity, curling or buckling of paper or the failure of the ink to dry arise.

### Textiles

Like paper, textiles are sensitive to changes in humidity and to a lesser extent changes in temperature. In modern textile plants, yarn moves at very high speeds and any changes in flexibility and strength of the yarn because of the change in humidity and temperature will thus affect the production.

### Precision Parts and Clean Rooms

In manufacturing of precision metal parts air conditioning helps to (a) keep the temperature uniform so that the metal will not expand and contract, (b) maintain a humidity so that rust is prevented and (c) filter the air to minimize dust.

### Photographic Products

Raw photographic materials deteriorate fast in high humidity and temperatures. Other materials used in coating film also require a careful control of temperature. Therefore, photographic-products industry is a large user of refrigeration and air conditioning.

### Computer Rooms

In computer rooms, air conditioning controls temperature, humidity and cleanliness of the air. Some electronic components operate in a faulty manner if they become too hot. One means of preventing such localized high temperature is to maintain the air temperature in the computer room in the range of 20 to 23 $^0$C. The electronic components in the computer functions favorably at even lower temperatures, but this temperature is a compromise with the lowest comfortable temperature for occupants. A relative humidity of about 65% is maintained for comfort condition.

### Air Conditioning of Vehicles

For comfortable journey, planes, trains, ships, buses are air conditioned. In many of these vehicles the major contributor to the cooling load is the heat from solar radiation and in case of public transportation, heat from people.

**Figure 1.8 : Air Conditioning is a must for a Computer Room**

**Food Storage and Distribution**

Many meats, fish, fruits and vegetables are perishable and their storage life can be extended by refrigeration. Fruits, many vegetables and processed meat, such as sausages, are stored at temperatures just slightly above freezing to prolong their life. Other meats, fish, vegetables and fruits are frozen for many months at low temperatures until they are defrosted and cooked by consumer.

## SAQ 3

(a) List some applications of air conditioning.

(b) What are the temperature and humidity required for the comfort air conditioning?

(c) Why is the air conditioning required in the computer room?

(d) How refrigeration helps in the preservation of food products?

(e) Why air conditioning is essential in preservation of photographic materials?

(f) Why is air conditioning important for textile industries?

# 1.4 UNIT OF REFRIGERATION AND COP

The standard unit of refrigeration is *ton refrigeration* or simply *ton* denoted by TR. It is equivalent to the rate of heat transfer needed to produce 1 ton (2000 lbs) of ice at 32 $^0$F from water at 32 $^0$F in one day, i.e., 24 hours. The enthalpy of solidification of water from and at 32 $^0$F in British thermal unit is 144 Btu/lb. Thus

$$1\ \text{TR} = \frac{2000\,\text{lb} \times 144\,\text{Btu/lb}}{24\,\text{hr}}$$

$$= 12000\ \text{Btu/hr} = 200\ \text{Btu/min}$$

In general, 1 TR means 200 Btu of heat removal per minute. Thus if a refrigeration system is capable of cooling at the rate of 400 Btu/min, it is a 2 ton machine. A machine of 20 ton rating is capable of cooling at a rate of 20 × 200 = 4000 Btu/min. This unit of refrigeration is currently in use in the USA, the UK and India. In many countries, the standard MKS unit of kcal/hr is used. In the MKS it can be seen that

$$1\ \text{TR} = 12000\ \text{Btu/hr} = \frac{12000}{3.968} = 3024.2\ \text{kcal/hr}$$

$$= 50.4\,\text{kcal/min} \approx 50\,\text{kcal/min}$$

If Btu ton unit is expressed into SI system, it is found to be 210 kJ/min or 3.5 kW.

Refrigeration effect is an important term in refrigeration that defines the amount of cooling produced by a system. This cooling is obtained at the expense of some form of energy. Therefore, it is customary to define a term called coefficient of performance (COP) as the ratio of the refrigeration effect to energy input.

$$\text{COP} = \frac{\text{Refrigeration effect}}{\text{Energy input}}$$

While calculating COP, both refrigeration effect and energy input should be in the same unit.

**SAQ 4**

(a) What is ton of refrigeration?

(b) What is refrigeration effect?

(c) How is the COP of a refrigeration system defined?

## 1.5 ILLUSTRATIVE PROBLEMS

**Example 1.1**

A refrigeration system produces 40 kg/hr of ice at 0°C from water at 25°C. Find the refrigeration effect per hour and TR. If it consumes 1 kW of energy to produce the ice, find the COP. Take latent heat of solidification of water at 0°C as 335 kJ/kg and specific heat of water 4.19 kJ/kg °C.

**Solution**

Heat removal rate to form 40 kg of ice at 0°C from water at 25°C

$Q_c$ = sensible cooling from 25°C to 0°C + latent heat of solidification of water

= 40 kg/hr × (25 – 0) °C × 4.19 kJ/kg. °C + 40 kg/hr × 335 kJ/kg

= 4190 kJ/hr + 13400 kJ/hr

= 17590 kJ/hr

Refrigeration effect ($Q_C$) = 17590 kJ/hr

We know that 1 TR = 210 kJ/min = 12600 kJ/hr

Therefore, TR equivalent to 17590 kJ/hr = $\frac{17590\,\text{kJ/hr}}{12600\,\text{kJ/hr}} = 1.396$

$$\text{COP} = \frac{\text{Refrigeration effect}}{\text{Energy input}} = \frac{17590\,\text{kJ/hr}}{1 \times 3600\ \text{kJ/hr}} = 4.886$$

**Example 1.2**

200 kg of ice at – 10°C is placed in a bunker to cool some vegetables. 24 hours later the ice has melted into water at 5°C. What is the average rate of cooling in kJ/hr and TR provided by the ice? Assume

Specific heat of ice, $c_{p,i}$ = 1.94 kJ/kg °C

Specific heat of water, $c_{p,w}$ = 4.1868 kJ/kg °C

Latent heat of fusion of ice at 0°C, $L$ = 335 kJ/kg.

**Solution**

Rate of heat addition to 200 kg ice at – 10°C to form water at 5°C

$Q_C$ = (sensible heat gain of ice from – 10°C to 0°C + latent heat of melting of ice + sensible heat gain of water from 0°C to 5°C)/time

= (200 kg × (0 – (– 10)) °C × 1.94 kJ/kg. °C + 200 kg × 335 kJ/kg + 200 kg × (5 – 0) °C × 4.1868 kJ/kg. °C)/24 hr

= 3127.78 kJ/hr

Capacity = $\frac{3127.78\,\text{kJ/hr}}{12600\,\text{kJ/hr}}$ = 0.248 TR

## 1.6 SUMMARY

In this unit a brief introduction to the concept of refrigeration and air conditioning was presented. Most of us are familiar with the household refrigerator which has become an indispensable part of our lives. This refrigerator is a perfect example of a mechanism utilizing the laws of thermodynamics in performing some useful work. These refrigerators work on the vapor compression refrigeration cycle which is the subject of the next unit. In the subsequent units, we will go into a deeper understanding of the refrigeration and air conditioning process from an engineering point of view.

The subject of refrigeration can be better studied if we follow the progress made by the refrigeration industry through the ages. The student should be able to appreciate better the importance of refrigeration in our industries and also in our daily life after they have gone through this unit. This unit presents the basic terminologies and concepts associated with refrigeration and air conditioning. Subsequent units will build on these concepts and develop upon them. At the end of this unit, the student should be familiar with different terms such as COP, ton of refrigeration and refrigeration effect. These terms are very frequently used in the study of the various refrigeration cycles and form the basis upon which a practicing engineer can decide on a refrigeration system depending upon the particular needs.

## 1.7 ANSWERS TO SAQs

Refer the relevant preceding texts in the unit or other useful books on the topic listed in the section “Further Readings” to get the answers of the SAQs.