REFRIGERATION

1. Introduction

Refrigeration is the process of removing heat from matter that may be a solid, liquid, or gas. Removing heat from the matter cools it, ie, lowers its temperature. There are a number of ways of lowering temperatures, some of which are of historical interest only. In some older methods, lowering of temperature may be accomplished by the rapid expansion of gases under reduced pressures. Thus, cooling may be brought about by compressing air, removing the excess heat produced in compressing it, and then permitting it to expand.

Lowering of temperatures may be realized by adding certain salts, eg, sodium nitrate, sodium thiosulfate (hypo), and sodium sulfite, to water. The same effect is produced, but to a lesser extent, by dissolving common salt or calcium chloride in water.

Two common methods of refrigeration are natural and mechanical. In natural refrigeration, ice has been used since ancient times and is still widely used. In this natural technique, the forced circulation of air passes around blocks of ice. Some of the heat of the circulating air is transferred to the ice, thus the air is cooled, particularly for air conditioning applications. In mechanical refrigeration, a refrigerant is a substance capable of transferring heat that absorbs it at low temperatures and pressures to a condensing medium; in the region of transfer, the refrigerant is at higher temperatures and pressures. By means of expansion, compression, and a cooling medium, eg, air or water, the refrigerant removes heat from a substance and transfers it to the cooling medium.

Refrigeration is used in industry for cooling and freezing of products, condensing vapors, maintaining environmental conditions, and for cold storage. The number of different applications is huge and they are a major consumer of electricity. In some sectors, particularly food, drink, and chemicals, it represents a significant proportion of overall site energy costs (up to 90% in the case of some cold storage facilities) (1).

Presently, the refrigeration industry urgently needs (*1*) technical information on the refrigeration systems, system components, and technical and operational aspects of such systems and components; (*2*) procedures for energy and energy analyses of refrigeration systems for system design and optimization; (*3*) application of optimum refrigeration techniques; (*4*) techniques for the measurement and evaluation of the components' performance; (*5*) methodology for the use of the cooling data to design an efficient and effective refrigeration system and/or to improve the existing refrigeration systems; and (*6*) environmentally benign refrigerants.

The main goal of this article is to introduce fundamental aspects and concepts of refrigeration systems and applications and to discuss refrigeration cycles, major refrigeration system components (eg, compressors, condensers, evaporators, throttling devices), and their technical and operational aspects, auxiliary refrigeration system components, refrigerants, and some alternative refrigerants. For further details on these along with practical examples and applications, see Ref. 1.

2. Refrigerants

In general, refrigerants are well known as the fluids absorbing heat during evaporation and provide a cooling effect. During this phase there is a change from liquid to vapor. These refrigerants are commonly used in refrigeration, air conditioning, and heat pump systems, as well as process systems.

2.1. Classification of Refrigerants.

This section focuses only on the primary refrigerants that can be classified into the following five main groups:

1. *Halocarbons*: These contain one or more of the three halogens chlorine, fluorine, or bromine, and are widely used in refrigeration and air conditioning systems as refrigerants. These are more commonly known by their trade names, such as Freon, Arcton, Genetron, Isotron, and Uron. Numerical indication is preferable in practice. In this group, the halocarbons, consisting of chlorine, fluorine, and carbon, have been the most commonly used refrigerants (so-called *chlorofluorocarbons*, *CFCs*). The CFCs have been commonly used as refrigerants, solvents, and foam blowing agents. The most common CFCs have been CFC-11 or R-11, CFC-12 or R-12, CFC-113 or R-113, CFC-114 or R-114, and CFC-115 or R-115.
2. *Hydrocarbons (HCs)*: These are the compounds that mainly consist of carbon and hydrogen. The HCs include methane, ethane, propane, cyclopropane, butane, and cyclopentane. Although HCs are highly flammable, they may offer advantages as alternative refrigerants because they are inexpensive to produce and they have zero ozone depletion potential, very low global warming potential, and low toxicity. There are several types of HC families, eg, hydrobromofluorocarbons (HBFCs) are the compounds consisting of hydrogen, bromine, fluorine, and carbon; hydrochlorofluorocarbons (HCFCs) are the compounds consisting of hydrogen, chlorine, fluorine, and carbon; hydrofluorocarbons (HFCs) are the compounds consisting of hydrogen, fluorine, and carbon; methyl bromide (CH_3Br) is a compound consisting of carbon, hydrogen, and bromine; and methyl chloroform (CH_3CCl_3) which is a compound consisting of carbon, hydrogen, and chlorine.
3. *Inorganic compounds*: In spite of the early invention of many inorganic compounds, today they are still used in many refrigeration, air conditioning, and heat pump applications as refrigerants. Some examples are ammonia (NH_3), water (H_2O), air ($0.21\,O_2 + 0.78\,N_2 + 0.01\,Ar$), carbon dioxide ($CO_2$), and sulfur dioxide ($SO_2$). Among these compounds, ammonia has received the greatest attention for practical applications and is still of interest even today. Below, the focus is briefly on three compounds of this family: ammonia, carbon dioxide, and air.
4. *Azeotropic mixtures*: An azeotropic refrigerant mixture consists of two substances having different properties, but behaving as a single substance. The two substances cannot be separated by distillation. The most common azeotropic refrigerant is R-502, which contains 48.8% R-22 and 51.2% R-115. Its coefficient of performance is higher than that of R-22 and its lesser toxicity provides an opportunity to use this refrigerant in household refrigeration systems and the food refrigeration industry. Some other examples

of azeotropic mixtures are R-500 (73.8% R-12 + 26.2% R-152a), R-503 (59.9% R-13 + 40.1% R-23), and R-504 (48.2% R-32 + 51.8% R-115).

5. *Nonazeotropic mixtures*: A nonazeotropic mixture is a fluid consisting of multiple components of different volatiles that, when used in refrigeration cycles, change composition during evaporation (boiling) or condensation. These mixtures are also called zeotropic mixtures or blends. The application of nonazeotropic mixtures as refrigerants (eg, R-11, R-12, R-22, and R-114) in refrigeration systems has been widely used since the beginning of the twentieth century. Although many nonazeotropic mixtures (eg, R-11 + R-12, R-12 + R-22, R-12 + R-114, R-13B1 + R-152a, R-22 + R-114 and R-114 + R-152a, etc) have been well known, during the past decade research and development has mainly focused on three mixtures, R-12 + R-114, R-22 + R-114, and R-13B1 + R-152a. It is clear that the heat transfer phenomena during the phase change of nonazeotropic mixtures are more complicated than with single-component refrigerants.

2.2. Secondary Refrigerants. Secondary refrigerants play a role in carrying heat from an object or a space being cooled to the primary refrigerant or the evaporator of a refrigeration system. During this process, the secondary refrigerant has no phase change. In the past, the most common secondary refrigerants were brines, which are water and salt (eg, sodium chloride and calcium chloride) solutions. Today, they are still used in spite of their corrosive effects. Also, the antifreezes, which are solutions of water and ethylene glycol, propylene glycol, or calcium chloride, are widely used as secondary refrigerants. Of these fluids, propylene glycol has the unique feature of being safe when in contact with food products. Recently, dichloromethane (CH_2Cl_2), trichloroethylene (C_2HCl_3), alcohol solutions, and acetone have also been used in some special applications.

2.3. Refrigerant–Absorbent Combinations. The refrigerant–absorbent combinations (so-called working fluids) are basically used in absorption refrigeration and heat pump systems. Inorganic and organic groups are major sources of the refrigerants and absorbents. Some organic groups for refrigerants are amines, alcohols, halogens, and hydrocarbons, and for absorbents, alcohols, ethers, alcohol–ethers, amides, amines, amine–alcohols, esters, ketones, acids, or aldehydes can be used. Two well-known examples are ammonia–water and water–lithium bromide. The absorbent is also called the solvent. The absorbent should have a greater chemical affinity for the refrigerant than the ordinary law of solubility would indicate. Very little heat is released when the freons, nitrogens, or certain other gases are dissolved in water. However, water has a high chemical affinity for ammonia, and considerable heat is evolved during absorption. For example, at 15°C one unit of water can absorb ~ 800 units of ammonia. Thus the quantity of heat released in absorption is a crude measure of the chemical affinity.

2.4. Stratospheric Ozone Layer Depletion as a Major Environmental Problem. Here, we explain some key components and their role before going into the details of stratospheric ozone depletion:

Ultraviolet (uv) radiation is a portion of the electromagnetic spectrum with wavelengths shorter than visible light. The sun produces uv, which is commonly split into three bands known as uva, uvb, and uvc:

- *uva*. This is a band of uv radiation with wavelengths from 320 to 400 nm produced by the sun and is not absorbed by ozone. This band of radiation has wavelengths just shorter than visible violet light.
- *uvb*. This is a band of uv radiation with wavelengths from 280 to 320 nm. The uvb is a kind of uv light from the sun (and sun lamps) that has several harmful effects, particularly effective at damaging DNA. It is a cause of melanoma and other types of skin cancer. It has also been linked to damage to some materials, crops, and marine organisms. The ozone layer protects the earth against most uvb coming from the sun. It is always important to protect oneself against uvb, even in the absence of ozone depletion, by wearing hats, sunglasses, and sunscreen. However, these precautions will become more important as ozone depletion worsens.
- *uvc*. This is a band of uv radiation with wavelengths shorter than 280 nm. Despite being extremely dangerous, it is completely absorbed by ozone and oxygen (O_2).

Stratosphere is a region of the atmosphere above the troposphere and extends from ~15 to 50 km in altitude. As a matter of fact, the stratosphere temperature increases with altitude, due to the absorption of uv light by oxygen and ozone. This creates a global inversion layer that impedes vertical motion into and within the stratosphere: Since warmer air lies above colder air in the upper stratosphere, convection is inhibited. The word stratosphere is related to the word stratification or layering.

Troposphere is a region of the atmosphere closest to the earth and extends from the surface up to ~10 km in altitude, although this height varies with latitude. Almost all weather takes place in the troposphere. Mt. Everest, the highest mountain on earth, is only 8.8-km high. Temperatures decrease with altitude in the troposphere. As warm air rises, it cools, falling back to earth. This process, known as convection, means there are huge air movements that mix the troposphere very efficiently.

Ozone is a gas composed of three atoms of oxygen, known as a bluish gas that is harmful to breathe. Nearly 90% of the earth's ozone is situated in the stratosphere and is referred to as the ozone layer. Ozone absorbs a band of uvb that is particularly harmful to living organisms. The ozone layer prevents most uvb from reaching the ground.

The *Ozone layer* is a region of the stratosphere containing the bulk of atmospheric ozone. The ozone layer lies ~15–40 km above the earth's surface, in the stratosphere. The ozone layer is between 2- and 5-mm thick in the stratosphere under normal temperature and pressure conditions and its concentration varies depending on the season, the hour of the day, and the location. The concentration is greatest at an altitude of ~25 km near the equator and at about an altitude of 16 km near the poles. The ozone comes mostly from the photodisassociation of oxygen by uv radiation of very short wavelength (ie, 200 μm).

The *stratospheric ozone layer depletion* is a chemical destruction of the stratospheric ozone layer beyond natural reactions and is known as one of the global environmental problems (Fig. 1). It has been shown that this issue is mainly caused by the ozone depletion substances (ODSs). Stratospheric ozone is constantly being created and destroyed through natural cycles. Various ODSs, however, accelerate the destruction processes, resulting in lower than normal ozone levels. Depletion of this layer by ODS will lead to higher uvb levels, which in turn will cause increased skin cancers and cataracts and potential damage to some marine organisms, plants, and plastics.

The *ozone-depleting substances* are the compounds that contribute to stratospheric ozone depletion. The ODSs include CFCs, HCFCs, halons, methyl bromide, carbon tetrachloride, and methyl chloroform. These substances are generally very stable in the troposphere and only degrade under intense uv light in the stratosphere. When they break down, they release chlorine or bromine atoms, which then deplete ozone.

Three decades ago, Rowland and Molina first launched a theory (2) that CFCs and some other anthropogenic trace gases in the atmosphere may act to deplete the stratospheric ozone layer by catalytic action of free chlorine. They predicted very rapid reduction of concentration despite having ozone measurements almost steady for nearly 50 years for the time, without any serious consideration. This theory brought in a new phase in the modeling of stratospheric chemistry and gave rise to renewed activities in the field. In fact, the most significant point that makes the conditions quite complicated is the natural air movement in all directions, air having nearly 40 different compounds giving several hundred possible reactions. That is why the models were extremely complex. The reduction in mean ozone level was estimated to be in the range between 0 and 10%, depending on the assumptions.

In the 1930s, Chapman described the reactions in ASHRAE (3): ozone is created in the upper stratosphere by short-wavelength uv radiation ($< \sim 240$ nano-40 nanometers) when it is absorbed by oxygen molecules (O_2), which dissociate to give oxygen (O) atoms. These atoms combine with other oxygen molecules and make ozone as follows:

$$O_2 + \text{uv} \longrightarrow 2\,O \quad \text{and} \quad O + O_2 \longrightarrow O_3$$

Sunlight with wavelengths between 240 and 320 nm is absorbed by ozone, which then falls apart to give an O atom and an O_2 molecule. Ozone is transformed back into oxygen if an O atom comes together with an O_3 as follows:

$$O_3 + \text{sunlight} \longrightarrow O + O_2 \quad \text{and} \quad O + O_3 \longrightarrow 2\,O_2$$

This cycle seems to combine with many others, particularly catalytic destructive actions. An example of ozone depletion:

$$R + O_3 \longrightarrow RO + O_2 \quad \text{and} \quad RO + O \longrightarrow R + O_2$$

where R may be nitrogen or hydroxide or chlorine radicals.

The CFCs are compounds with at least one chlorine, one fluorine, and one carbon atom in their molecule. Chlorine from the CFCs has been understood to lead to the depletion of ozone in the stratosphere. It is the chlorine that makes a substance ozone depleting; CFCs and HCFCs are a threat to the ozone layer, but HFCs are not.

If the ozone depletion continues, it is likely to have effects on the following (1):

- Human skin, with the development of skin tumors and more rapid aging of the skin.
- Human eyes, with an increase in cataracts.
- Human immunological system.
- Land and sea biomass, with a reduction in crop yields and in the quantity of phytoplankton.

The *ozone depletion potential* (ODP) is a number that refers to the amount of stratospheric ozone depletion caused by a substance. The ODP is the ratio of the impact on ozone of a chemical compared to the impact of a similar mass of R-11. Thus, the ODP of R-11 is defined to be 1.0. Other CFCs and HCFCs have ODPs that range from 0.01 to 1.0. The halons have ODPs ranging up to 10. Carbon tetrachloride has an ODP of 1.2, and methyl chloroform's ODP is 0.11. The HFCs have zero ODP because they do not contain chlorine. As an example, a compound with an ODP of 0.2 is, roughly, about one-fifth as harmful as R-11. The ODP of any refrigerant (ie, R-X) is defined as the ratio of the total amount of ozone destroyed by a fixed amount of R-X to the amount of ozone destroyed by the same mass of R-11, as follows:

$$\mathrm{ODP(R\text{-}X)} = (\text{Ozone loss because of R-X})/(\text{Ozone loss because of R-11}).$$

The CFCs are considered fully halogenated. This means that there are no hydrogen atoms, only halogens (chlorine, fluorine, bromine, etc). As mentioned earlier, the refrigerants with hydrogen atoms are known as HCFCs (eg, R-22, R-123, R-124, R-141b and R-142b); they are not fully halogenated and are less stable than CFCs. The computed ODP values for HCFC refrigerants are very low (on the order of 0.01–0.08) compared to the values estimated for CFCs (on the order of 0.7–1, for R-11, R-12, R-113, and R-114, and ~ 0.4 for R-115). It is for this reason that the Montreal Protocol had a main goal of phasing out CFC-type refrigerants. There is a family of refrigerants with an estimated ODP value of zero and without any chlorine, called HFCs. Some examples of HFCs mentioned above are R-125, R-134a, R-143a, and R-152a. Research and development activities have focused on the use of these ozone- and environment-friendly refrigerants.

2.5. Greenhouse Effect (Global Climate Change) as a Major Environmental Problem.

Although the term Greenhouse effect has generally been used for the role of the whole atmosphere (mainly water vapor and clouds) in keeping the surface of the earth warm, it has been increasingly associated with the contribution of CO_2 (currently, it is estimated that CO_2 contributes

$\sim 50\%$ to the anthropogenic greenhouse effect). However, several other gases, eg, CH_4, CFCs, halons, N_2O, ozone, and peroxyacetylnitrate (so-called *Greenhouse gases*) produced by the industrial and domestic activities, can also contribute to this effect, resulting in a rise in the earth's temperature. A schematic representation of this global problem is illustrated in Figure 2. In the Greenhouse effect phenomenon, the rays of the sun reach the earth and maintain an average temperature level of around $+15^\circ C$. A large part of the infrared (ir) rays reflected off the earth are caught by CO_2, H_2O, and other substances (including CFCs) present in the atmosphere and kept from going back out into space. The increase in the Greenhouse effect would result in a sudden rise in temperature, and it is very likely linked with human activity, in particular the emissions from fossil fuel consumption. Also, increasing the Greenhouse effect has resulted in the following:

- An intermediate warming of the atmosphere.
- A rise in the level of the ocean.
- Climatic effects (increases in drought, storms, hurricanes, etc).

Increasing atmospheric concentrations of CFCs have accounted for $\sim 24\%$ of the direct increase in the radiative heating from Greenhouse gases over the last decade. However, an observed decrease in stratospheric ozone, thought to be connected to increasing stratospheric chlorine from CFCs, suggests a negative radiative heating or cooling tendency over the last decade.

The release of CFCs into the atmosphere affects climate in two different ways (4):

- The CFCs are highly harmful Greenhouse gases (relative to CO_2), due to their stronger ir band intensities, stronger absorption features, and longer atmospheric lifetimes.
- The CFCs deplete the stratospheric ozone layer that affects earth surface temperature in two ways: more solar radiation reaching the surface lower troposphere system, resulting in a warmer climate and leading to lower stratospheric temperatures and, therefore, less ir radiation being passed to the earth's surface-lower troposphere system, resulting in lower ground-level temperatures.

Therefore, the net effect is dependent on the altitudes where the ozone change takes place.

The *global warming potential* (GWP) is a number that refers to the amount of global warming caused by a substance. The GWP is the ratio of the warming caused by a substance to the warming caused by a similar mass of CO_2. Thus, the GWP of CO_2 is defined to be 1.0. CFC-12 has a GWP of 8500, while CFC-11 has a GWP of 5000. Various HCFCs and HFCs have GWPs ranging from 93 to 12100. Water, a substitute in numerous end-uses, has a GWP of 0. GWP represents how much a given mass of a chemical contributes to global warming, over a given time period, compared to the same mass of CO_2. These values are calculated over a 100-year time horizon.

2.6. Alternative Refrigerants. There has been a need for the new, alternative substances to replace the fully halogenated refrigerants that are believed to contribute to atmospheric ozone depletion. In the past decade, many research and development studies on the synthesis and characterization of alternative refrigerants have been undertaken. The replacement of restricted ODSs by any alternative may involve substantial changes in the design of various components, eg, insulation, lubricants, heat exchangers, and motors. Tests must be done to optimize the system performance and to ensure the reliability and safety of the system. Several alternative refrigerants are already available on the market. Several people (5) have suggested natural refrigerants, ie, ammonia, propane, and CO_2 to replace ODSs. Here, we present R-134a as the most common alternate as well as some other potential replacements, including the natural substances, although there are so many alternates available ranging from application to application.

R-134a is an HFC refrigerant that has a boiling temperature of $-26.2°C$ ($-29.8°C$ for R-12) and a latent heat of 205 kJ/kg (159 kJ/kg for R-12) (6). This is a nonflammable and nontoxic substitute for R-12. R-134a has been widely used in household refrigerators and in automotive air conditioning, but there appears to be little benefit in using it in conventional air conditioning or refrigeration where reasonable condensing temperatures can be specified. The R-134a is suggested as a potential replacement for R-22 in packaged systems. However, the volumetric displacement of a compressor for R-134a must be $\sim 50\%$ larger than the displacement of an R-22 compressor of the same cooling capacity. Pressure drops in refrigerant tubing can have a significant effect on the COP of an R-134a system, so larger tubing may be needed than in R-22 systems. The R-134a is also acceptable as a substitute for R-400 (60/40% by weight) and R-114 in new industrial process air conditioning. The R-134a does not contribute to ozone depletion, which R-134a's GWP and atmospheric lifetime are close to those of other alternatives that are acceptable in this end-use. The R-134a is compatible with most existing refrigeration and air conditioning equipment parts, but it is not compatible with the mineral oils currently used in such systems. An appropriate ester-based, polyalkylene glycol-based, or other type of lubricant should be used.

R-123 is an HCFC that has a boiling point of 27.1°C (23.8°C for R-11), a latent heat of 175 kJ/kg at 15°C (194 kJ/kg for R-11), and a molecular weight of 153. It is suitable for use in chiller systems with centrifugal compressors, air conditioning, refrigeration, and heat pump systems. The R-123s environmental suitability as a replacement for R-11 is not in doubt. It has an ODP and a GWP < 0.02, compared with 1.0 for R-11, and does not present any flammability problem. About its toxicology, R-123 was assigned an allowable exposure limit of 100 parts per million (7). This means that a worker should not be continuously exposed to > 100 ppm of R-123 during any working day of 8–12 h. Regarding the safety issue, the requirements for handling both R-123 and R-11 refrigerants in charging and servicing equipment are the same. It was suggested that the paraffinic oils that are used with R-11 could also be used with R-123.

Nonazeotropic mixtures (eg, R-401A and R-401B) appear to be acceptable as a substitute for R-400 (60/40% by weight) and R-114 in retrofitted industrial process air conditioning. Note that different temperature regimes may affect the applicability of the above substitutes within these end-uses. The R-404A is also acceptable as a substitute for R-12 in new household refrigerators. None of this blend's constituents contains chlorine, and thus this blend poses no threat to stratospheric ozone. However, R-125 and R-143a have very high GWPs, and the GWP of HFC-134a is somewhat high. In addition, R-410A is also used to replace R-22 in high pressure unitary air conditioning applications.

Azeotropic mixtures have received some attention during the past decades as substitutes to replace harmful CFCs, eg, R-22 in air conditioning systems and R-12, R-22 and R-502 in household and industrial refrigeration systems. Also, R-507 is acceptable as a substitute for R-12 in new household refrigerators and for R-502 in cold store plants. It is an azeotropic blend by weight of 53% R-125 and 47% R-134a at atmospheric pressure. At lower temperatures the azeotropic range of the blend may vary from 40 to 60% R-134a by weight (8). Note that neither R-125 nor R-134a contains any chlorine, and ester oils can be used for lubrication. In terms of material compatibility (ie, corrosiveness) with seals and metals including copper and aluminium, R-507 is comparable to R-502 and retrofitting R-502 refrigeration plants for R-507 can easily be carried in accordance with the already familiar procedures for conversion from R-12 to R-134a. None of this blend's constituents contains chlorine. Thus, this blend poses no threat to the stratospheric ozone. However, R-125 and R-143a have very high GWPs. In many countries, recycling and reclamation of this blend is strongly recommended to reduce its direct global warming impact. Although R-143a is flammable, the blend is not. Leak testing has demonstrated that its composition never becomes flammable.

Ammonia (R-717) has been the most widely used of the classic alternative refrigerants. Two characteristics of R-717, the saturation pressure–temperature relationship and the volume flow rate per unit refrigeration capacity, are quite similar to those of R-22 and R-502. On the other hand, R-717 has some advantages over R-22 and R-502, such as lower cost, better cycle efficiency, higher heat transfer coefficients, higher critical temperature, greater detectability in the event of leaks, lower liquid pumping costs for liquid recirculation systems, more tolerance of water contamination, more favorable behavior with oil, zero ODP and GWP, and smaller refrigerant piping. After 120 years of extensive usage, a tremendous amount of practical experience exists with this refrigerant. There is no doubt about its excellent thermodynamic and transfer properties, which are greatly superior to those of the halocarbons, and its important practical advantages, eg, tolerance to normal lubricating oils and limited pollution with water, easy leak detection, and low price. All these factors contribute to its sustained popularity and wide application, in spite of the often expressed doubts about its safety. It is true that ammonia is poisonous and can burn with air, although it is quite difficult to ignite and will hardly sustain a flame by itself. The risk is strongly counteracted by the fact that it has an extremely strong odor, and that it is much lighter than air. A leak is easily detected by smell at a concentration far below a dangerous level, and a massive escape of ammonia rapidly disappears upward in the atmosphere. Accidents are therefore extremely rare.

Propane (R-290) has been used as a working fluid in large refrigeration plants for many years, notably in the petrochemical processing industry. It has excellent thermodynamic properties approaching those of ammonia, but the explosion and fire hazard is much more severe. This will certainly limit its application in the normal refrigeration field, although the risk should not be overestimated. Combustible gases are commonplace in many technical applications and do not cause many problems when simple precautions are observed. Propane has a special advantage for use in turbo compressors due to its near ideal molar mass. It has been a potential candidate to substitute R-12 in household refrigerators and freezers, and also perhaps in small air conditioning units.

CO_2 (R-744) was a commonly used refrigerant from the late nineteenth and well into the twentieth century. Due to its complete harmlessness it was the generally preferred choice for usage on board ships, while ammonia was more common in stationary applications. By the advent of the Freons and R-12 in the first place, CO_2 was rapidly abandoned, and it has nearly been forgotten in the course of the last 40–50 years. The main reasons for this development were certainly the rapid loss of capacity at high cooling water temperatures in the tropics, and not less the failure of the manufacturers to follow modern trends in compressor design toward more compact and price effective high speed types. Time is now ripe for a reassessment of this refrigerant for application with present day technology.

2.7. Selection of Refrigerants. In the selection of an appropriate refrigerant for use in a refrigeration or heat pump system, there are many criteria to be considered. Briefly, the refrigerants are expected to meet the following conditions (1): ozone layer and environment friendly; low boiling temperature; low volume of flow rate per unit cooling and heat transfer capacity; vaporization pressure lower than atmospheric pressure; high heat of vaporization; nonflammable and nonexplosive; noncorrosive and nontoxic; nonreactive and nondepletive with the lubricating oils of the compressor; nonacidic in case of a mixture with water or air; chemically stable; suitable thermal and physical properties (eg, thermal conductivity, viscosity); commercially available; easily detectable in case of leakage; low cost; recyclable; and safe disposal.

2.8. Lubricating Oils and Their Effects. It is known that the lubricating oil contained in the crankcase of the compressor is generally in contact with the refrigerant. When oil dissolves in the refrigerant, it affects the thermodynamic properties of the refrigerant. The main effect is the reduction of the vapor pressure by the amount depending on the nature of the oil and the refrigerant and on how much oil dissolves. It is important to state that the refrigerants are expected to be chemically and physically stable in the presence of oil, so that neither the refrigerant nor the oil is adversely affected by the relationship.

3. Main Refrigeration Systems and Cycles

The main goal of a refrigeration system that performs the reverse effect of a heat engine is to remove the heat from a low level temperature medium (heat source) and to transfer this heat to a higher level temperature medium (heat sink). Figure 3 shows a thermodynamic system acting as a refrigeration machine. The absolute temperature of the source is T_{L} and the heat transferred from the source is the refrigeration effect (refrigeration load) Q_{L}. On the other side, the heat rejection to the sink at the temperature T_H is Q_H as the condenser heat load. Both effects are accomplished by the work input W. For continuous operation, the First Law of Thermodynamics is applied to the system.

Refrigeration is one of the most important thermal processes in various practical applications, ranging from space conditioning to food cooling. In these systems, the refrigerant is used to transfer the heat. Initially, the refrigerant absorbs heat because its temperature is lower than the heat source's temperature and the temperature of the refrigerant is increased during the process to a temperature higher than the heat sink's temperature. Therefore, the refrigerant delivers the heat.

The main refrigeration systems can be categorized as follows: vapor–compression refrigeration systems; absorption refrigeration systems; air-standard refrigeration systems; jet ejector refrigeration systems; thermoelectric refrigeration; and thermoacoustic refrigeration.

Although in this part the focus will be on vapor–compression refrigeration systems and their components, other types will be explained briefly later.

3.1. Refrigeration System Components. There are several mechanical components required in a refrigeration system. Major components of a vapor–compression refrigeration system are compressor, condenser, evaporator, and throttling device. In this section, some auxiliary equipment associated with these major components as refrigerant lines and piping, refrigerant capacity control devices, receivers, and accumulators will be discussed also.

In the selection of any component for a refrigeration system, there are a number of factors that need to be considered carefully, including: maintaining total refrigeration availability while the load varies from 0 to 100%; frost control for continuous performance applications; variations in the affinity of oil for refrigerant caused by large temperature changes, and oil migration outside the compressor crankcase; selection of cooling medium: (*1*) direct expansion refrigerant, (*2*) gravity or pump recirculated or flooded refrigerant, or (*3*) secondary coolant (brines, eg, salt and glycol); system efficiency and maintainability; type of condenser: air, water or evaporatively cooled; compressor design (open, hermetic, semihermetic motor drive, reciprocating, screw, or rotary); system type (single stage, single economized, compound, or cascade arrangement); selection of refrigerant (note that the type of refrigerant is basically chosen based on operating temperature and pressures).

Compressors. In a refrigeration cycle, the compressor has two main functions within the refrigeration cycle. One function is to pump the refrigerant vapor from the evaporator so that the desired temperature and pressure can be maintained in the evaporator. The second function is to increase the pressure of the refrigerant vapor through the process of compression, and simultaneously increase the temperature of the refrigerant vapor. By this change in pressure the superheated refrigerant flows through the system.

Refrigerant compressors, which are known as the heart of the vapor–compression refrigeration systems, can be divided into two main categories as displacement compressors, and dynamic compressors. Both displacement and dynamic compressors can be hermetic, semihermetic, or open types. The compressor both pumps refrigerant round the circuit and produces the required substantial increase in the pressure of the refrigerant. The refrigerant chosen and the operating temperature range needed for heat pumping generally lead to a need for a compressor to provide a high pressure difference for moderate flow rates, and this is most often met by a positive displacement compressor using a reciprocating piston. Other types of positive displacement compressor use rotating vanes or cylinders or intermeshing screws to move the refrigerant. In some larger applications, centrifugal or turbine compressors are used, which are not positive displacement machines, but accelerate the refrigerant vapor as it passes through the compressor housing. These various compressor types are illustrated in Fig. 4.

In the market, there are many different types of compressor available, in terms of both enclosure type and compression system. Here are some options for evaluating the most common types:

- Reciprocating compressors are positive displacement machines, available for every application. The efficiency of the valve systems has been improved significantly on many larger models. Capacity control is usually by cylinder unloading (a method that reduces the power consumption almost in line with the capacity).
- Scroll compressors are rotary positive displacement machines with a constant volume ratio. They have good efficiencies for air conditioning and high temperature refrigeration applications. They are only available for commercial applications and do not usually have built-in capacity control.

The refrigerant compressors are expected to meet the following requirements: high reliability; long service life; easy maintenance; easy capacity control; quiet operation; compactness; and low cost.

In the selection of a proper refrigerant compressor, the following criteria are considered: refrigeration capacity; volumetric flow rate; compression ratio; and thermal and physical properties of the refrigerant.

Condensers. There are several condensers to be considered when making a selection for installation. They are air-cooled, water-cooled, shell and tube, shell and coil, tube within a tube (double pipe), and evaporative condensers. Each type of condenser has its own unique application. Some determining factors include the size and the weight of the unit, weather conditions, location (city or rural), availability of electricity, and availability of water. A wide variety of condenser configurations are employed in the process industry. Selection of condenser type is not easy and depends on the following criteria: condenser heat capacity; condensing temperature and pressure; the flow rates of refrigerant and coolant; design temperature for water and/or air; operation period; and climatic conditions.

Condensers utilized in the refrigeration industry are commonly of three types, as follows: water-cooled condensers; air-cooled condensers; and evaporative condensers.

Common types of water- and air-cooled refrigerant condensers for commercial refrigeration use are shell and tube, blow-through, horizontal air-flow; shell and coil, draw-through, vertical air-flow; and tube in tube, static, or forced air-flow.

The type of condenser selected depends largely on the following considerations: size of the cooling load; refrigeration used; quality and temperature of available cooling water (if any); and amount of water that can be circulated, if water use is acceptable.

Water-Cooled Condensers. Water-cooled condensers are of many different types as shown in Figure 5. The most common condensers are generally shell-and tube-type heat exchangers with refrigerant flow through the shell and water (as coolant) flow through the tubes (SST type in Fig. 5). The lower portion of the shell acts as a liquid receiver. These condensers are widely used in large heat capacity refrigerating and chilling applications. If a water-cooled condenser is used, the following criteria must be examined: requirement of cooling water for heat rejection; utilization of a cooling tower if inexpensive cooling water is available; requirement of auxiliary pumps and piping for recirculating cooling water; requirement of water treatment in water recirculation systems; space requirements; maintenance and service situations; and provision of freeze protection substances and tools for winter operation.

Air-Cooled Condensers. The air-cooled condensers are commonly used in domestic, commercial, and industrial refrigerating, chilling, freezing, and air conditioning systems with a common capacity of 20–120 tons. The centrifugal fan air-cooled condensers (with a capacity of 3–100 tons) are particularly used for heat recovery and auxiliary ventilation applications. In general, they utilize outside air as the cooling medium. Fans draw air past the refrigerant coil and the latent heat of the refrigerant is removed as sensible heat by the air stream. Some advantages of air-cooled condensers are no water requirement; standard outdoor installation; elimination of freezing, scaling, and corrosion problems; elimination of water piping, circulation pumps, and water treatment; low installation cost; and low maintenance and service requirement.

On the other hand, they have some disadvantages, which are high condensing temperatures; high refrigerant cost because of long piping runs; high power requirements per kW of cooling; high noise intensity; and multiple units requirement for large-capacity systems.

Evaporative Condensers. Evaporative condensers are apparently water-cooled designs and work on the principle of cooling by evaporating water into a moving air stream. The effectiveness of this evaporative cooling process depends on the wet bulb temperature of the air entering the unit, the volume of air flow and the efficiency of the air–water interface. These condensers use water sprays and air flow to condense refrigerant vapors inside the tubes. The condensed refrigerant drains into a tank called a liquid receiver. Refrigerant subcooling can be accomplished by piping the liquid from the receiver back through the water sump, where additional cooling reduces the liquid temperature even further.

Evaporators. Evaporator can be considered the point of heat capture in a refrigeration system and provides the cooling effect required for any particular application. There are almost as many different types of evaporators as there are applications of heat exchangers. However, evaporators are divided into two categories, eg, (*1*) direct cooler evaporators that cool air that in turn cools the product and (*2*) indirect cooler evaporators that cool a liquid, such as brine solution, that in turn cools the product. Normally, the proper evaporator comes with the system. However, there may be an occasion when designing a system, so one will need to determine the requirements and select the proper evaporator from a manufacturer's catalog or manual. In practice, liquid coolers, air coolers, and/or gas coolers are commonly used as evaporators for cooling, refrigerating, freezing, and air conditioning applications:

Heat Pipes. During the past two decades, heat pipe technology has received a great deal of attention and miniature and conventional heat pipes can be successfully used in many industrial applications, especially in the cooling of electronic components and devices. A heat pipe consists typically of a sealed container with a wicking material. The container is evacuated and filled with just enough liquid to fully saturate the wick. As illustrated in Figure 6, a heat pipe consists of three distinct regions: an evaporator or heat addition region of the container, a condenser or heat rejection region, and an adiabatic or isothermal region. When the evaporator region is exposed to a high temperature heat is added and the working fluid in the wicking structure is heated until it evaporates. The high temperature and the corresponding high pressure in this region cause the vapor to flow to the cooler condenser region, where the vapor condenses, giving up its latent heat of vaporization. The capillary forces existing in the wicking structure then pump the liquid back to the evaporator. The wick structure thus ensures that the heat pipe can transfer heat if the heat source is below the cooled end (bottom heat mode) or if it is above the cooled end (top heat mode).

Some of the well-known working fluids (so-called heat pipe liquids) are liquid hydrogen, ammonia, acetone, methanol, water, sodium, potassium, lithium, mercury, and silver. In addition, a number of heat pipe wall and wick materials are recommended, eg, aluminum, carbon steel, nickel, copper, tungsten, molybdenum, and refractory metals and alloys. Much research effort has been carried out to find the most efficient and reliable working fluids and wall–wick materials and the best configurations of the heat pipes for various ranges of temperature, depending on the applications.

Throttling Devices. In practice, throttling devices, called either expansion valves or throttling valves, are used to reduce the refrigerant condensing pressure (high pressure) to the evaporating pressure (low pressure) by a throttling operation and regulate the liquid–refrigerant flow to the evaporator to match the equipment and load characteristics. These devices are designed to proportion the rate at which the refrigerant enters the cooling coil to the rate of evaporation of the liquid refrigerant in the coil; the amount depends, of course, on the amount of heat being removed from the refrigerated space. The most common throttling devices are as follows: thermostatic expansion valves; constant pressure expansion valves; float valves; and capillary tubes.

A practical refrigeration system may consist of a large range of mechanical and electronic expansion valves and other flow control devices for small- and large-scale refrigeration systems, comprising thermostatic expansion valves (Fig. 7), solenoid valves, thermostats and pressostats, modulating pressure regulators, filter driers, liquid indicators, nonreturn valves and water valves, and furthermore, decentralized electronic systems for full regulation and control.

Auxiliary Devices. There are a number of auxiliary devices used in the refrigeration systems as follows:

- *Accumulators*: The purpose of the accumulator is to act as a reservoir to temporarily hold the excess oil–refrigerant mixture and to return it at a rate that the compressor can safely handle. Some accumulators include a heat-exchanger coil to aid in boiling-off the liquid refrigerant while subcooling the refrigerant in the liquid line, thus helping the system to operate more efficiently. Proper installation of a suction accumulator in the suction line just after the reversing valve and before the compressor helps eliminate the possible damage. Accumulators should be selected according to the tonnage, evaporator temperature, and holding capacity.
- *Receivers*: These are required on refrigeration systems that use an expansion valve for refrigerant control. The receiver provides a place to store the excess refrigerant in the system when the expansion valve restricts the flow to the evaporator. Receivers are not required, however, when using a capillary metering system. In addition to accommodating fluctuations in the refrigerant charge, the receiver aims to maintain the condenser drained of liquid, thereby preventing the liquid level from building up in the condenser and reducing the amount of effective condenser surface area.
- *Oil separators*: These provide oil separation and limit oil carry-over to $\sim 0.0003–0.001\%$ of the total amount of refrigerant, depending on various system characteristics, eg, operating conditions, refrigerant, start–stop and load–unload frequency, etc. These separators are normally used for a large variety of refrigerants, eg, ammonia, R-134a and propane. All the separators require the mounting of an external float assembly to control return from the separator to the compressor.
- *Strainers*: These are used to remove foreign matter, eg, dirt and metal chips from the refrigerant lines. If left in the system, unwanted matter could clog the small orifices of the flow-control devices and check valves and also enter the compressor. Various types are available, eg, straight-through sealed type, cleanable angle type, and the cleanable Y type.
- *Driers*: In refrigeration systems, moisture is the single most detrimental factor. A unit can stand only a very small amount of moisture. For this reason, the majority of both field- and factory-assembled refrigeration systems are equipped with driers. Some factors influencing the selection of the correct size of drier are type and amount of refrigerant, refrigeration system tonnage, line size, and allowable pressure drop. When the refrigerant type, line size, and equipment application are known, the drier is generally selected on the basis of recommended capacities, which take into account both drying and refrigerant flow capacity.
- *Check valves*: These are used for two essential goals: (*1*) to cause the refrigerant to flow through the flow-control device and (*2*) to allow the refrigerant to bypass the flow-control device. These valves are installed in a loop that bypasses the flow-control device and only open when pressure is exerted in the right direction; therefore, they should be installed with the arrow pointing in the proper direction of refrigerant flow at the point of installation. In operation, the refrigerant pushes either against the valve seat to close it tighter or against its face to cause it to open and allow refrigerant

to pass through. These valves are usually spring loaded and will open when the pressure difference on the seat reaches ~100–135 kPa.

- *Solenoid valves*: These are extensively used in all types of refrigeration applications. These valves are employed as electrically operated line stop valves and perform in the same manner as hand shut-off valves. These valves are convenient for remote applications due to the fact that these are electrically operated and controlled easily.
- *Defrost controller*: A defrost controller with timer operates various control valves and fan relays to quickly and efficiently remove frost and ice accumulation from evaporator surfaces. There are four easy-to-set defrost steps: pump out, hot gas, equalize, and fan delay.

Figure 8 shows a comprehensive diagram of a practical vapor compression refrigeration system with all control devices.

3.2. Vapor–Compression Refrigeration Systems.

In practical applications, vapor–compression refrigeration systems are the most commonly used refrigeration systems, and each system employs a compressor. In a basic vapor–compression refrigeration cycle as shown in Figure 9, four major thermal processes take place as follows:

1. *Evaporation*: Unlike freezing and melting, evaporation and condensation occur at almost any temperature and pressure combination. Evaporation is gaseous escape of molecules from the surface of a liquid and is accomplished by the absorption of a considerable quantity of heat without any change in temperature. Liquids (eg, refrigerants) evaporate at all temperatures with increased rates of evaporation occurring at higher temperatures. The evaporated gases exert a pressure called the vapor pressure. As the temperature of the liquid rises, there is a greater loss of the liquid from the surface, which increases the vapor pressure. In the evaporator of a refrigeration system, a low-pressure cool refrigerant vapor is brought into contact with the medium or matter to be cooled (ie, heat sink), absorbs heat, and hence boils, producing a low-pressure saturated vapor.
2. *Compression*: Using shaft work of a compressor raises the pressure of the refrigerant vapor obtained from the evaporator. The addition of heat may play a role in raising the pressure. Increasing the gas pressure raises the boiling and condensing temperature of the refrigerant. When the gaseous refrigerant is sufficiently compressed its boiling point temperature is higher than the heat sink's temperature.
3. *Condensation*: This is a process of changing a vapor into a liquid by extracting heat. The high pressure gaseous refrigerant, which carries the heat energy absorbed in the evaporator and the work energy from the compressor, is brought into the condenser. The condensing temperature of the refrigerant is higher than that of the heat sink and therefore heat transfer condenses the high pressure refrigerant vapor to the high pressure saturated liquid. The heat source has been cooled by heat pumping to the heat sink. Instead of using a condenser to reject heat, the refrigerant vapor can be discharged to the atmosphere, but this technique is impractical.

Condensing the refrigerant gas allows reuse at the beginning of the next cycle. In some practical applications, it is desired that the condenser cools the refrigerant further, below the condensation temperature. This is called subcooling, which is usually observed in the condenser to reduce flashing when the refrigerant pressure is reduced in the throttling device. This method provides a reduction in the amount of gas entering the evaporator and hence an improvement in the system performance.

4. *Expansion*: The condensed refrigerant liquid is returned to the beginning of the next cycle. A throttling device, eg, a valve, orifice plate, or capillary tube for the expansion process, is used to reduce the pressure of the refrigerant liquid to the low pressure level and the boiling temperature of the refrigerant to below the temperature of the heat source. Energy losses through this pressure reduction must be offset by additional energy input at the pressurization stage.

Figure 9**a** shows a schematic diagram of a basic vapor–compression refrigeration system. For better understanding, this refrigeration cycle is shown by temperature–entropy (T–s) and pressure–enthalpy (log P–h) diagrams as given in Figure 9**b** and **c**. Under the steps given above, the operation of this system is

- *(1-2) Reversible adiabatic compression.* From the evaporator, low pressure saturated refrigerant vapor comes to the compressor and is compressed into the condenser by volume reduction and increased pressure and temperature.
- *(2-3) Reversible heat rejection at constant pressure.* From the compressor, high pressure refrigerant vapor enters the condenser and is liquefied by employing water or air.
- *(3-4) Irreversible expansion at constant enthalpy.* From the condenser, high pressure saturated refrigerant liquid passes through an expansion valve and its pressure and temperature are reduced.
- *(4-1) Reversible heat addition at constant pressure.* From the expansion valve, low pressure refrigerant liquid arrives in the evaporator. It boils here and in the process absorbs heat from the surrounding medium, thereby providing a cooling effect.

Practical Vapor–Compression Refrigeration Cycle. There are some clear differences between the practical (actual) cycle and the theoretical cycle (standard ideal cycle) primarily due to pressure and temperature drops associated with refrigerant flow and heat transfer to or from the surroundings. Figure 10 shows an actual vapor compression refrigeration cycle. The refrigerant vapor entering the compressor is normally superheated. During the compression process, due to the irreversibilities and heat transfer either to or from the surroundings, depending on the temperatures of the refrigerant and the surroundings, entropy may increase or decrease (for the irreversibility and heat transferred to the refrigerant), as shown by the two dashed lines 1-2 and 1-2′. The pressure of the liquid leaving the condenser becomes less than the pressure of the vapor entering, and the temperature of the refrigerant in the condenser is somewhat higher than that of the surroundings to which heat is being transferred. As always, the temperature of the liquid leaving the condenser is lower than the saturation temperature. It may drop even more in the piping between the condenser and expansion valve. This represents a gain, however, because as a result of this heat transfer the refrigerant enters the evaporator with a lower enthalpy, which permits more heat to be transferred to the refrigerant in the evaporator. There is also some pressure drop as the refrigerant flows through the evaporator. It may be slightly superheated as it leaves the evaporator, and through heat transferred from the surroundings its temperature increases in the piping between the evaporator and the compressor. This heat transfer represents a loss, because it increases the work of the compressor, since the fluid entering it has an increased specific volume.

A practical commercial mechanical vapor–compression refrigeration system is shown in Figure 11. In the system shown, it is possible to use the temperature, pressure, and latent heat of vaporization properly. This system utilizes a water-cooled condenser, and water removes heat from the hot refrigerant vapor to condense it. Therefore, the water carries away the heat that is picked up by the evaporator as the refrigerant boils. The refrigerant is then recirculated through the system again to carry out its function to absorb heat in the evaporator.

Superheating and Subcooling. Superheating (referring to superheating of the refrigerant vapor leaving evaporator) and subcooling (referring to subcooling of refrigerant liquid leaving the condenser) are apparently two significant processes in practical vapor–compression refrigeration systems and are applied to provide better efficiency (COP) and to avoid some technical problems, as are explained below.

Superheating: During the evaporation process the refrigerant is completely vaporized partway through the evaporator. As the cool refrigerant vapor continues through the evaporator, additional heat is absorbed to superheat the vapor. Under some conditions, such pressure losses caused by friction increase the amount of superheat. If the superheating takes place in the evaporator, the enthalpy of the refrigerant is raised, extracting additional heat and increasing the refrigeration effect of the evaporator. If it is provided in the compressor suction piping, no useful cooling occurs. In some refrigeration systems, liquid–vapor heat exchangers can be employed to superheat the saturated refrigerant vapor from the evaporator with the refrigerant liquid coming from the condenser (Fig. 12). As can be seen from Figure 12, the heat exchanger can provide high system performance. Refrigerant superheating can also be obtained in the compressor. In this case, the saturated refrigerant vapor enters the compressor and is superheated by increasing the pressure, leading to the temperature increase. Superheating obtained from the compression process does not improve the cycle efficiency, but results in larger condensing equipment and large compressor discharge piping. The increase in the refrigeration effect obtained by superheating in the evaporator is usually offset by a decrease in the refrigeration effect in the compressor. Because the volumetric flow rate of a compressor is constant, the mass flow rate and the refrigeration effect are reduced by decreases in the refrigerant density caused by the superheating. In practice, it is well known that there is a loss in the refrigerating capacity of 1% for every 2.5°C of superheating in the suction line. Insulation of the suction lines is a solution to minimize undesirable heat gain. The desuperheating is a process to remove excess heat from superheated refrigerant vapor, and if accomplished by using an external effect it will be more useful to the COP. Desuperheating is often considered impractical, owing to the low temperatures ($< 10°C$) and small amount of available energy.

Subcooling: This is a process of cooling the refrigerant liquid below its condensing temperature at a given pressure (Fig. 12). Subcooling provides 100% refrigerant liquid to enter the expansion device, preventing vapor bubbles from impeding the flow of refrigerant through the expansion valve. If the subcooling is caused by a heat transfer method external to the refrigeration cycle, the refrigerant effect of the system is increased, because the subcooled liquid has less enthalpy than the saturated liquid. Subcooling is accomplished by refrigerating the liquid line of the system, using a higher temperature system. Simply, we can state that subcooling cools the refrigerant more and provides the following accordingly: increase in energy loading; decrease in electrical usage; reducing pulldown time; more uniform refrigerating temperatures; and reduction in the initial cost.

3.3. Multistage Refrigeration Systems. Multistage refrigeration systems are widely used where ultralow temperatures are required, but cannot be obtained economically through the use of a single-stage system. This is due to the fact that the compression ratios are too large to attain the temperatures required to evaporate and condense the vapor. There are two general types of such systems: cascade and multistage. The multistage system uses two or more compressors connected in series in the same refrigeration system. The refrigerant becomes more dense vapor while it passes through each compressor. Note that a two-stage system (Fig. 13) can attain a temperature of approximately −65°C and a three-stage refrigeration system about −100°C, respectively.

Single-stage vapor–compression refrigerators are used by cold storage facilities with a range of +10 to −30°C. In this system, the evaporator installed within the refrigeration system and the ice making unit, as the source of low temperature, absorbs heat. Heat is released by the condenser at the high pressure side.

In cases where large temperature and pressure differences exist between the evaporator and the condenser, multistage vapor–compression systems are employed accordingly. For example, if the desired temperature of a refrigerator (ie, freezer) is below −30°C, a several-stage compression system is required in order to prevent the occurrence of high compression ratios. Some disadvantages of a high compression ratio are decrease in the compression efficiency; increase in the temperature of the refrigerant vapor from the compressor; and increase in energy consumption per unit of refrigeration production.

Figure 13**a** shows a schematic diagram of a two-stage vapor–compression refrigeration unit that can provide temperatures below −30°C (approximately to −50°C), and its $T–s$ and log $P–h$ diagrams are shown in Figure 13**b** and **c**. This system also uses an intercooler with air.

As an example, three-stage refrigeration systems can provide an evaporator temperature of −100°C. In the two-stage unit shown, the refrigerant is compressed in the first stage and, after being desuperheated by an intercooler, is further compressed in the second stage. An intercooler is used between the two compression stages for reducing the compression work. In other words, a booster (first-stage) compressor and a gas–liquid intercooler are attached to the single-stage cycle. The intercooler subcools the refrigerant liquid supplied to the evaporator by vaporizing a portion of the refrigerant after the first throttling stage. The flash gas returns at an intermediate point in the compression process in order to improve the compression efficiency by cooling the superheated gas. Not only a compressor, but a set of compressors are required to use in each stage, depending on the capacity and temperature. In large systems with a number of evaporators and large compression (temperature) ratios, the number of intercoolers and compression stages yields increased system efficiency, and hence increased performance.

3.4. Cascade Refrigeration Systems.

For some industrial applications that require moderately low temperatures (with a considerably large temperature and pressure difference), single-vapor compression refrigeration cycles become impractical. One of the solutions for such cases is to perform the refrigeration in two or more stages (ie, two or more cycles) that operate in series. These refrigeration cycles are called cascade refrigeration cycles. Therefore, cascade systems are employed to obtain high temperature differentials between the heat source and heat sink and are applied for temperatures ranging from −70 to 100°C. Application of a three-stage compression system for evaporating temperatures below −70°C is limited, due to difficulties with refrigerants reaching their freezing temperatures. Impropriety of three-stage vapor compression systems can be avoided by applying a cascade vapor–compression refrigeration system.

Cascade refrigeration systems are commonly used in the liquefaction of natural gas and some other gases. A large-capacity industrial cascade refrigeration system is shown in Figure 14.

The most important advantage of these cascade systems is that refrigerants can be chosen with the appropriate properties, avoiding large dimensions for the system components. In these systems, multiple evaporators can be utilized in any one stage of compression. Refrigerants used in each stage may be different and are selected for optimum performance at the given evaporator and condenser temperatures.

Conventional single compressor, mechanical refrigeration system condensing units are capable of achieving temperatures of about −40°C. If lower temperatures are required, then cascade refrigeration systems must be used. A two-stage cascade system uses two refrigeration systems connected in series to achieve temperatures of around −85°C. There are single compressor systems that can achieve temperatures colder than −100°C, but they are not widely used. These systems are sometimes referred to as auto cascading systems. The main disadvantage of such systems is that it requires the use of a proprietary blend of refrigerant. This characteristic results in three service-related problems:

- A leak in the system can easily cause the loss of only some of the refrigerant making up the blend (due to the refrigerant blend which is made up of different types of refrigerant with different boiling points), resulting an imbalance in the ratio of the remaining refrigerants. To return the system to proper operation, all of the remaining refrigerant must be replaced with a new and potentially costly charge to insure a proper blend ratio.

- The blend is proprietary and may not be readily available from the traditional refrigerant supply sources and therefore may be hard to obtain and costly.
- These types of cascade systems are not widely used; it is hard to find well-qualified field service staff that are familiar with repair and maintenance procedures.

Of course, these and other issues can cause undesirable expense and downtime.

Two-Stage Cascade Systems. A two-stage cascade system employs two vapor–compression units working separately with different refrigerants, and interconnected in such a way that the evaporator of one system is used to serve as condenser to a lower temperature system (ie, the evaporator from the first unit cools the condenser of the second unit). In practice, an alternative arrangement utilizes a common condenser with a booster circuit to provide two separate evaporator temperatures. In fact, the cascade arrangement allows one of the units to be operated at a lower temperature and pressure than would otherwise be possible with the same type and size of single-stage system. It also allows two different refrigerants to be used, and it can produce temperatures below $-150°C$. Figure 15 shows a two-stage cascade refrigeration system, where condenser B of system 1 is being cooled by evaporator C of system 2. This arrangement enables us to reach ultralow temperatures in evaporator A of the system. For a schematic system shown in Figure 16, the condenser of system I, called the first or high pressure stage, is usually fan cooled by the ambient air. In some cases, a water supply may be used, but air-cooling is much more common. The evaporator of system I is used to cool the condenser of system II called the second or low pressure stage. The unit that makes up the evaporator of system I and the condenser of system II is often referred to as the interstage or cascade condenser. As stated earlier, cascade systems generally use two different refrigerants (ie, one in each stage). One type is used for the low stage and a different one for the high stage. The reason why two refrigeration systems are used is that a single system cannot economically achieve the high compression ratios necessary to obtain the proper evaporating and condensing temperatures. It is clear from the $T–s$ diagram of the two-stage cascade refrigeration system, as shown in Figure 16, that the compressor work decreases and the amount of refrigeration load (capacity) in the evaporator increases as a result of cascading. Therefore, cascading improves the performance.

Three-Stage (Ternary) Cascade Refrigeration System. Cascade refrigeration cycles are commonly used in the liquefaction of natural gas, which consists basically of hydrocarbons of the paraffin series, of which methane has the lowest boiling point at atmospheric pressure. Refrigeration down to that temperature can be provided by a ternary cascade refrigeration cycle using propane, ethane, and methane, whose boiling points at standard atmospheric pressure are 231.1, 184.5, and 111.7 K, respectively (10). A simplified basic diagram for such as a cascade cycle is shown in Figure 17. In the operation, the compressed methane vapor is first cooled by heat exchange with the propane in the propane evaporator before being condensed by heat exchange with the ethane in the ethane evaporator, thus reducing the degree of irreversibility involved in the cooling and condensation of the methane. Also, because of the high temperature after compression, the gas leaving each compressor passes first through a water-cooled aftercooler. In large-scale plant of this type, the compressors become rotary turbo-machines instead of the reciprocating type ones.

4. Absorption Refrigeration Systems (ARS)

Although the principle of the absorption refrigeration cycle has been known since the early 1800s, the first one was invented by French engineer Ferdinand P.E. Carre in 1860, an intermittent crude ammonia absorption apparatus based on the chemical affinity of ammonia for water, and produced ice on a limited scale. The first five ARS units Carre produced were used to make ice, up to 100 kg/h. In the 1890s, many large ARS units were manufactured for chemical and petroleum industries. The development of ARSs slowed to a standstill by 1911 as vapor compression refrigeration systems came to the forefront. After 1950, large ARSs gained in popularity. In the 1970s, the market share of ARSs dropped rapidly due to the oil crisis, and hence government regulations. Due to increasing energy prices and environmental impact of refrigerants, during the past decade ARSs have received increasing attention. So, many companies have concentrated on ARSs and now do research and development on these while the market demand increases dramatically.

The concept of absorption refrigeration developed well before the advent of electrically driven refrigerators. In the last decades, the availability of cheap electricity has made absorption systems less popular. Today, improvements in absorption technology, the rising cost, and the environmental impact of generating electricity are contributing to the increasing popularity of absorption systems. The ARSs for industrial and domestic applications have been attracting increasing interest throughout the world because of the following advantages over other refrigeration systems: quiet operation, high reliability, long service life, efficient and economic use of low grade energy sources (eg, solar energy, waste energy, geothermal energy), easy capacity control, no cycling losses during on–off operations, simpler implementation, and meeting the variable load easily and efficiently.

It is considered that the ARS is similar to the vapor–compression refrigeration cycle (using the evaporator, condenser, and throttling valve as in a basic vapor–compression refrigeration cycle), except that the compressor of the vapor–compression system is replaced by three main elements, an absorber, a solution pump, and a generator. Three steps, absorption, solution pumping, and vapor release, take place in an ARS. In Figure 18, a basic ARS, which consists of an evaporator, a condenser, a generator, an absorber, a solution pump, and two throttling valves, is schematically shown. The strong solution (a mixture strong in refrigerant), which consists of the refrigerant and absorbent, is heated in the high pressure portion of the system (the generator). This drives refrigerant vapor off the solution. The hot refrigerant vapor is cooled in the condenser until it condenses. Then the refrigerant liquid passes through a throttling valve into the low pressure portion of the system, the evaporator. The reduction in pressure through this valve facilitates the vaporization of the refrigerant, which ultimately effects the heat removal from the medium. The desired refrigeration effect is then provided accordingly. The weak solution (weak in refrigerant) flows down through a throttling valve to the absorber. After the evaporator, the cold refrigerant comes to the absorber and is absorbed by this weak solution (ie, absorbent), because of the strong chemical affinity for each other. The strong solution is then obtained and is pumped by a solution pump to the generator, where it is again heated, and the cycle continues. It is significant to note that the system operates at high vacuum at an evaporator pressure of $\sim 1.0\,\text{kPa}$; the generator and the condenser operate at $\sim 10.0\,\text{kPa}$.

Recently, there has been increasing interest in the industrial and domestic use of the ARSs for meeting cooling and air conditioning demands as alternatives, due to a trend in the world for rational utilization of energy sources, protection of the natural environment, and prevention of ozone depletion, as well as reduction of pollution.

The absorption cycle is a process by which the refrigeration effect is produced through the use of two fluids and some quantity of heat input, rather than electrical input as in the more familiar vapor compression cycle. In ARSs, a secondary fluid (ie, absorbent) is used to circulate and absorb the primary fluid (ie, refrigerant), which is vaporized in the evaporator. The success of the absorption process depends on the selection of an appropriate combination of refrigerant and absorbent. The most widely used refrigerant and absorbent combinations in ARSs have been ammonia–water and lithium bromide–water. The lithium bromide–water pair is available for air conditioning and chilling applications ($>4^\circ\text{C}$, due to the crystallization of water). Ammonia–water is used for cooling and low temperature freezing applications ($<0^\circ\text{C}$).

The absorption cycle uses a heat-driven concentration difference to move refrigerant vapors (usually water) from the evaporator to the condenser. The high concentration side of the cycle absorbs refrigerant vapors (which, of course, dilutes that material). Heat is then used to drive off these refrigerant vapors thereby increasing the concentration again.

5. Air-Standard Refrigeration Systems

The air-standard refrigeration cycles are also known as the reverse Brayton cycles. In these systems, refrigeration is accomplished by means of a noncondensing gas (eg, air) cycle rather than a refrigerant vapor cycle. While the refrigeration load per kilogram of refrigerant circulated in a vapor–compression cycle is equal to a large fraction of the enthalpy of vaporization, in an air cycle it is only the product of the temperature rise of the gas in the low side heat exchanger and the specific heat of the gas. Therefore, a large refrigeration load requires a large mass rate of circulation. In order to keep the equipment size smaller, the complete unit may be under pressure, which requires a closed cycle. The throttling valve used for the expansion process in a vapor–compression refrigeration cycle is usually replaced by an expansion engine (eg, expander) for an air cycle refrigeration system. The work required for the refrigeration effect is provided by the gas refrigerant. These systems are of great interest in applications where the weight of the refrigerating unit must be kept to a minimum, eg, in aircraft cabin cooling.

A schematic arrangement of a basic air-standard refrigeration cycle and its T–s diagram is shown in Figure 19. This system has four main elements: a compressor that raises the pressure of the refrigerant from its lowest to its highest value (eg, isentropic compression:1-2); an energy output heat exchanger where the high temperature of the refrigerant is lowered (eg, isobaric heat rejection: 2-3); an expander where the pressure and temperature of the refrigerant are reduced (eg, isentropic expansion: 3-4); and an energy input heat exchanger that raises the temperature of the refrigerant at a constant pressure (eg, isobaric heat input: 4-1). This input is known as refrigeration load.

The utilization of air as a refrigerant becomes more attractive when a double purpose is to be met. This is so in the case of air conditioning, when the air can be both the refrigerating and the air conditioning medium. Figure 20 shows an air standard refrigeration cycle using a heat exchanger and its T–s diagram. Furthermore, air-standard refrigeration cycle is commonly used in the liquefaction of air and other gases, and also in certain cases where refrigeration is needed, eg, aircraft cooling systems.

6. Steam Jet Ejector Refrigeration Systems

In steam jet refrigeration systems, water can be used as the refrigerant. Like air, it is perfectly safe. These systems were applied successfully to refrigeration in the early years of this century. At low temperatures the saturation pressures are low (0.008129 bar at 4°C) and the specific volumes are high (157.3 m^3/kg at 4°C). The temperatures that can be attained using water as a refrigerant are not low enough for most refrigeration applications, but are in the range that may satisfy air conditioning, cooling, or chilling requirements. Also, these systems are used in some chemical industries for several processes, eg, the removal of paraffin wax from lubricating oils. Note that steam jet refrigeration systems are not used when temperatures $< 5°\mathrm{C}$ are required. The main advantages of this system are the utilization of mostly low grade energy and relatively small amounts of shaft work.

Steam jet refrigeration systems use steam ejectors to reduce the pressure in a tank containing the return water from a chilled water system. The steam jet ejector utilizes the energy of a fast-moving jet of steam to capture the flash tank vapor and compress it. Flashing a portion of the water in the tank reduces the liquid temperature. Figure 21 presents a schematic arrangement of a steam jet refrigeration system for water cooling. In the system shown, high pressure steam expands while flowing through the nozzle **1**. The expansion causes a drop in pressure and an enormous increase in velocity. Due to the high velocity, flash vapor from the tank **2** is drawn into the swiftly moving steam and the mixture enters the diffuser **3**. The velocity is gradually reduced in the diffuser, but the pressure of the steam at the condenser **4** is increased 5–10 times more than that at the entrance of the diffuser (eg, from 0.01 to 0.07 bar). This pressure value corresponds to the condensing temperature of 40°C. This means that the mixture of high pressure steam and the flash vapor may be liquefied in the condenser. The latent heat of condensation is transferred to the condenser water, which may be at 25°C. The condensate **5** is pumped back to the boiler, from which it may again be vaporized at a high pressure. The evaporation of a relatively small amount of water in the flash tank (or flash cooler) reduces the temperature of the main body of water. The cooled water is then pumped as the refrigeration carrier to the cooling-load heat exchanger.

An ejector was invented by Sir Charles Parsons ~1901 for removing air from steam engine condensers. In ~1910, the ejector was used by Maurice Leblanc in the steam ejector refrigeration system. It experienced a wave of popularity during the early 1930s for air conditioning large buildings. Steam ejector refrigeration cycles were later supplanted by systems using mechanical compressors. Since that time, development and refinement of ejector refrigeration systems have been almost at a standstill as most efforts have been concentrated on improving vapor compression cycles (11).

7. Thermoelectric Refrigeration

This type of system is used to move heat from one area to another by use of electrical energy. The electrical energy, rather than the refrigerant, serves as a carrier. The essential use of thermoelectric systems has been in portable refrigerators, water coolers, cooling of scientific apparatus used in space exploration, and in aircraft. The main advantage of this system is that there are no moving parts. Therefore, the system is compact, quiet, and needs little service.

Thermoelectric coolers are solid-state equipment used in applications where temperature stabilization, temperature cycling, or cooling below ambient are required. There are many products using thermoelectric coolers, including CCD (charge coupled device) cameras, laser diodes, microprocessors, blood analyzers, and portable picnic coolers.

Thermoelectrics are based on the Peltier Effect, discovered in 1834, by which direct current (dc) current applied across two dissimilar materials causes a temperature differential. The Peltier effect is one of the three thermoelectric effects, the other two being known as the Seebeck and Thomson effect. Whereas the last two effects act on a single conductor, the Peltier effect is a typical junction phenomenon (12).

The typical thermoelectric module is manufactured using two thin ceramic wafers with a series of P and N doped bismuth–telluride semiconductor materials sandwiched between them. The ceramic material on both sides of the thermoelectric adds rigidity and the necessary electrical insulation. The N-type material has an excess of electrons, while the P-type material has a deficit of electrons. One P and one N make up a couple, as shown in Figure 22. The thermoelectric couples are electrically in series and thermally in parallel. A thermoelectric module can contain one to several hundred couples. As the electrons move from the P-type material to the N-type material through an electrical connector, the electrons jump to a higher energy state absorbing thermal energy (cold side). Continuing through the lattice of material, the electrons flow from the N-type material to the P-type material through an electrical connector, dropping to a lower energy state and releasing energy as heat to the heat sink (hot side).

Thermoelectrics can be used to heat and to cool, depending on the direction of the current. In an application requiring both heating and cooling, the design should focus on the cooling mode. Using a thermoelectric in the heating mode is very efficient because all the internal heating (joulian heat) and the load from the cold side is pumped to the hot side. This reduces the power needed to achieve the desired heating. The appropriate thermoelectric for an application depends on at least three parameters. These parameters are the hot surface temperature, the cold surface temperature, and the heat load to be absorbed at the cold surface.

8. Thermoacoustic Refrigeration

Thermoacoustic refrigeration is considered a new technology, attaining cooling without the need for refrigerants. The basic mechanism is very simple and efficient. A loudspeaker creates sound in a hollow tube that is filled with an ordinary gas. In fact, thermoacoustic refrigeration utilizes high density sound waves to transfer heat due to the thermoacoustic effect (ie, acoustic energy). Therefore, the working fluid in this system is acoustically driven gas. The process itself utilizes standing acoustic waves in an enclosed cavity to generate the mechanical compression and expansion of a working fluid (gas in this case) needed for the cooling cycle. The technique has the potential for high efficiency operation without the need for cooling liquids or mechanical moving parts. These factors make the concept amenable to miniaturization to chip-scale dimensions for thermal management of electronic components.

The interaction between acoustics and thermodynamics has been known ever since the dispute between Newton and Laplace over whether the speed of sound was determined by the adiabatic or isothermal compressibility of air. At the present time, the efficiency of thermoacoustic refrigerators is 20–30% lower than their vapor compression refrigerators (13). Part of that lower efficiency is due to the intrinsic irreversibilities of the thermoacoustic heat transport process. These intrinsic irreversibilities are also the favorable aspects of the cycle, since they make for mechanical simplicity, with few or no moving parts. A greater part of the inefficiency of current thermoacoustic refrigerators is simply due to technical immaturity. With time, improvements in heat exchangers and other subsystems should narrow the gap. It is also likely that the efficiency in many applications will improve due only to the fact that thermoacoustic refrigerators are well suited to proportional control. One can easily and continuously control the cooling capacity of a thermoacoustic refrigerator so that its output can be adjusted accurately for varying load conditions. This could lead to higher efficiencies than for conventional vapor compression chillers that have constant displacement compressors and are therefore only capable of binary (on–off) control. Proportional control avoids losses due to the start-up surges in conventional compressors and reduces the inefficiencies in the heat exchangers, since such systems can operate over smaller temperature gaps between the coolant fluid and the heat load. Figure 23 shows a thermoacoustic refrigerator developed Garrett and co-workers at Pennsylvania State University.

Although thermoacoustic refrigerators have not been widely commercialized yet and are considered to be still at a developmental stage, it is known that they can be used for any kind of cooling. Conventional, single-stage, electrically operated thermoacoustic refrigerators can reach cold-side temperatures two-thirds to three-quarters of ambient, so they are not well suited to cryogenic applications below $-40°C$. However, thermoacoustically driven pulse-tube style refrigerators can reach the cryogenic temperatures required to liquefy air or natural gas. In their early commercial stages, they will probably be limited to niche applications, eg, in military systems that are required to operate in closed environments and food merchandizing, where toxicity is an important issue. As global environmental mandates and legislations–amendments become essential, one can expect the scope of thermoacoustic applications to expand both domestically and in emerging markets.

9. Food Refrigeration

Today, a wide variety of methods are available to maintain and enhance the appearance and taste of food. Food processing and preservation methods also create products that are convenient for consumers, eg, products that are ready to eat or require minimal preparation and cooking. Combining these methods with modern distribution networks makes seasonal crops available year-round in grocery stores all over the world.

Although food preservation techniques, eg, freezing and canning, are the results of relatively new food science technology, the preservation of food products has been practiced since the beginning of mankind by many methods, eg, sun drying, salting, smoking, and food fermentation. Many years ago our ancestors used chilling and freezing techniques for food preservation, eg, the use of water–ice taken from frozen lakes for chilling fish and meat. The technology of food preservation advanced dramatically with the discovery of microorganisms late in the eighteenth century and the appreciation of their role in food deterioration that followed. Research on food preservation technologies usually focuses on one of two aspects: the selection of process conditions to minimize product quality loss or the development of engineering design methodologies to ensure that the required process conditions can be achieved at low cost. Within the latter aspect heat transfer is usually the major concern. Heat must be removed from the product in chilling or freezing, and the product is subsequently to be maintained at constant temperature in storage. There are also important moisture-transfer effects, particularly evaporation from the product surface.

The means of preservation by drying, salting, smoking, cooking, etc, are often nutritionally less desirable and alter the taste of the produce; since they are generally less expensive, they are useful in feeding the population. But applying refrigeration results in foods of higher value.

The cooling of fruits and vegetables implies removal of the field heat before processing, transporting, or storing. Cooling inhibits growth of decay-producing microorganisms and restricts enzymatic and respiratory activity during the postharvest holding period, inhibits water loss, reduces ethylene production, and reduces the sensitivity of products to ethylene. The holding period may be the relatively short time required to transport and sell or process the product, or it may include a long-term storage period as well. It is important to mention that slowing down metabolism can give rise to physiological disorders that are called *cold storage injuries*. For this reason, the cooling temperature and exposing period must be suitable for the produce held.

The uses of refrigeration include the storage and preservation of foodstuffs, the maintenance of comfortable living conditions and industrial applications. The economic impact of refrigeration technology throughout the world is already very impressive and more important than is generally believed. It is therefore the refrigeration industry called by many as the *invisible industry*. The importance of refrigeration is bound to increase since it will be an essential factor in solving two major problems of the future: (*1*) the supply of enough food and (*2*) the development of new energy sources. The future's food supply in particular depends on the availability of sufficient energy. At present, fossil fuels carry the main load, but in the course of the present century, renewable energy sources and new energy sources will have to be commissioned. Refrigeration technology will play a key role in this development. It is therefore clear that refrigeration technology is used in countless ways to improve living conditions. It is essential to the development of new energy systems and rational conservation of perishable foods. Much remains to be done, however, to improve the efficiency of currently available processes and to develop new ones.

9.1. Food Precooling and Cooling. Precooling, chilling, is a cooling process in which the field temperature of the fruits and vegetables is reduced to the approximately optimum storage and/or transportation temperature (ie, chilling temperature) in the shortest time possible after harvest in the field prior to the storage and/or transportation. The main objective of this kind of treatment is to reduce the rates of biochemical and microbiological reactions and changes in order to prevent spoilage of produce, maintain its quality (all possible preharvest freshness and flavor), and extend its storage life (14–20).

Harvesting should be conducted in early morning hours to minimize field heat and the refrigeration load requirement on precooling equipment. Harvested products should be protected from the sun with a covering until they are placed in the precooling facility. Many products are field or shed packed and then precooled. Wirebound wood or nailed crates or wax impregnated fiberboard boxes are used for packed products that are precooled with water or ice after packing. Precooling of products packed in shipping containers and stacked in unitized pallet loads is especially important as air circulation around and through the packaging may be limited during transportation and storage.

Precooling is particularly important for products that produce a lot of heat. The following are examples of products that have high respiration rates and short transit and storage lives: artichokes, brussels sprouts, onions (green), asparagus, carrots (bunched), okra, beans (lima), corn (sweet), parsley, beans (snap), endive, bean sprouts, raspberries, blackberries, lettuce, spinach, broccoli, mushrooms, strawberries, watercress, etc (21).

Fresh produce (or any perishable item) continues to breathe or respirate after it has been harvested. As it respirates, it breaks down. Fresh produce is precooled to reduce the temperature of the produce, slow the respiration rate, and slow down product degradation. In practice, a proper temperature management through the distribution chain allows the consumers to buy the freshest possible produce anywhere.

Factors, eg, maturity, ripeness, harvesting date, variety, and origin, influence the optimum storage temperature and maximum storage lives of fruits and vegetables. The optimum storage temperature and storage life are influenced by, eg, ripeness, variety, harvesting date, and origin.

Precooling is the first postharvest operation in the cold chain. Produces are living organisms that even after harvesting have an active metabolism. In addition, respiration, heat and respiratory gases, and certain metabolic products, eg, carbonic acid and ethylene gases, are released during storage with undesirable consequences to the quality. It is found that a delay of 1 h to start precooling of grapes after the harvest reduces the shelf-life of grapes by a few days. All these undesirable effects are temperature dependent; the higher the temperature the larger the damage, culminating in product quality degradation and shortening of shelf-life. Therefore, by quick and uniform cooling after harvesting and subsequent maintaining of the products at optimum temperature the metabolic process is largely inactivated and the produce is brought to a dormant condition. Hence, produce can be stored for a longer period of time without losing its freshness.

Food Precooling/Cooling Systems. Precooling, the rapid removal of heat from freshly harvested vegetables, allows the grower to harvest produce at optimum maturity with greater assurance that it will reach the consumer at maximum quality.

The major types of precooling methods, namely, hydrocooling, contact icing, air cooling, hydraircooling (wet air), and vacuum cooling, are widely used in practice. Each of the above methods has its own advantages, disadvantages, suitability, or otherwise to a particular product. It is found that invariably forced air-cooling or wet air-cooling can be used for precooling of all types of products as it offers the following advantages. The following is a brief summary of these precooling methods:

- Room cooling: stacking containers of products in a refrigerated room. Some products are misted or sprayed with water during room cooling.
- Forced air or wet pressure cooling: drawing air through stacks of containers of products in a refrigerated room. For some products, water is added to the air. Forced air cooling can take 1 or 2 h depending on the amount of packaging, while room cooling may take 24–72 h. Packaging must allow ventilation of heat for these methods to be successful.
- Hydrocooling: flushing product in bulk tanks, bins, or shipping containers with a large quantity of ice water. In hydrocooling, fruits and vegetables are cooled by direct contact with cold water flowing through the packed containers and absorbing heat directly from the produce. Products and packaging must be able to withstand direct water contact in hydrocooling.
- Vacuum cooling: removing heat from products packed in shipping containers by drawing a vacuum in a chamber. The vacuum cooling process produces rapid evaporation of a small quantity of water, lowering the temperature of the product to the desired level. In vacuum cooling, it is

necessary that the products have a large surface area, low density, and high moisture content. The boxes and wrapping must allow ventilation of heat.

- Hydrovacuum cooling: adding moisture to products packed in shipping containers before or during the vacuum process, to speed the removal of heat.
- Package or contact icing: injecting slush or crushed ice into each shipping container of product. Some operations use bulk containers. In contact, icing crushed ice is placed in the package or spread over a stack of packages to precool the contents. Package icing provides effective cooling and a high relative humidity for products and packaging that can withstand direct contact with ice.

One of the above precooling methods may be selected by considering a number of criteria, including: the cooling rate; the type of commodity and subsequent storage; the nature, value, and quantity of the product; shipping conditions; equipment and operating costs; cost of labor; convenience; effectiveness; applicability; efficient energy use; operating conditions; personal preference; and product requirements.

9.2. Food Freezing. Freezing is a refrigeration process used to reduce the temperature of all parts of the produce below the freezing point. Freezing a product consists of converting the major part of the water contained in tissues into ice. The freezing point depends on the concentrations of dissolved substances and not on water content. To the degree to which the product is cooled below its freezing point an increasing quantity of water is transformed into ice crystals. The crystals are smaller and cause less injury to the tissues if the freezing is rapid enough. The concentration of the residual solutions increases during this operation; this is why a great degree of lowering of temperature is necessary to freeze the maximum amount of water. Below −30°C the content of ice hardly increases at all, and there remains a fraction of water that cannot be frozen. Frozen fruits and vegetables have no further metabolic activity. Freezing permits most perishable foods to be kept for several months. The freezing storage period depends on the kind of product and the level of the temperature.

The rate of freezing of foods is dependent primarily on several factors, eg, the freezing method, the temperature, the circulation of air or refrigerant (or cryogenics), the size and shape of package, and the kind of product. There are two basic ways to achieve food freezing, namely, quick or slow freezing. Quick freezing is the process by which the temperature of foods is lowered to −20°C within 30 min (22), and it may be achieved by direct immersion or indirect contact of foods with the refrigerants (or cryogenics) and the use of air blast freezing. Slow freezing is the process whereby the desired temperature is achieved within 3–72 h and is commonly used in domestic freezers. Quick freezing has some advantages over slow freezing from the standpoint of overall product quality. These two methods are compared in Table 1 (22,23).

Although freezing is an excellent preservation method against further deterioration, it also causes some undesirable changes in the product. Living tissues are destroyed in the process, and fruits and vegetables have a completely changed texture and much reduced quality in the thawed state. Despite these facts, freezing is considered certainly the most universally applicable and satisfactory of all long-term food preservation methods available.

Food Freezing Aspects. As mentioned above, freezing is one of the most important food refrigeration processes for long-term preservation and is applied to reduce the temperature of all parts of the food product below the freezing point. For most food products, the final quality of the frozen products is better if the freezing is done rapidly, especially if the zone 0 to −5°C is passed through rapidly and if the temperature is reduced to and maintained at a sufficiently low level. Today, if food is to be stored for more than several weeks, it is usually frozen. That is, the product's water content is changed to ice and its internal temperature is lowered to −18°C or below for storage. Practically, freezing consists of a reduction in temperature, generally to −18°C or below and crystallization of part of the water and some of solutes. Despite the fact that two or more of these events generally occur simultaneously, each one is taken separately into consideration.

The moisture content of food products may range between 50 and 95%, existing in different forms in the tissues. Freezing of a food product consists of converting the major part of the water contained in the tissues into ice. The point at which freezing begins is dependent directly on the concentrations of dissolved substances and not on water content. To the degree to which the product is cooled below its freezing point, an increasing quantity of water is transformed into ice crystals formed by pure water. The crystals are smaller and cause less injury to the tissues if the freezing is rapid enough. The concentration of the residual solutions increases during the process. This is why a great degree of lowering of temperature is required to freeze the maximum amount of water. Below −30°C the content of ice hardly increases at all, and there remains a fraction of water which cannot be frozen. Frozen fruits and vegetables have no further metabolic activity. The quantity of heat to be extracted from the food products to be frozen may be approximately derived by multiplying the latent heat of freezing water (~335,000 J/kg) by the water content of the food product. Below the freezing point, the specific heat has to be considered, as it is always less than that of ice, ie, 500 J/kg°C (23).

In freezing, there are two heat modes: (*1*) sensible heat that is first removed to lower the temperature of a product to the freezing point (including the removal of respiration heat produced), and (*2*) latent heat of crystallization that is then removed and ice crystals are formed. The latent heat of other compounds in the food (eg, fats), rather than that of water, must be removed before they solidify. As aforesaid above, most foods contain a large proportion of water, and the other compounds need a relatively small amount of heat of crystallization. A considerable amount of energy is needed to freeze food products due to the high specific heat and the high latent heat of fusion of water.

Many perishable fruits, vegetables, meat products, sea products, and poultry products are cooled below freezing temperatures in order to prevent their spoilage, maintain their quality, and extend their storage period. Freezing is one of the best methods by which foodstuffs are refrigerated at temperatures below −18°C. Applicable freezing temperatures of various food commodities are listed in Table 2.

It is important to point out that the effects of prolonged storage of food products during freezing are varied. In some cases, eg, in butter or fatty foods, the odor may become unpleasant (rancid). In other foods, eg, peaches, the appearance or color may become altered by an oxidation process. In some products, eg, fish, off-flavors may develop by both physical and chemical processes. The texture of asparagus may become undesirable. In addition, in many cases, the nutritive value of fruits and vegetables may be affected by hydrolysis and oxidation processes. Consequently, all these criteria related to food quality in terms of odor, appearance, flavor, texture, and nutritive value are of great significance for a food freezing process.

9.3. Cool and Cold Storage. Fresh vegetables are living organisms, and there is a continuation of life processes in the vegetable after harvest. Changes that occur in the harvested, nonprocessed vegetable include water loss, conversion of starches to sugars, conversion of sugars to starches, flavor changes, color changes, toughening, vitamin gain or loss, sprouting, rooting, softening, and decay. Some changes result in quality deterioration; others improve quality in those vegetables that complete ripening after harvest. Postharvest changes are influenced by such factors as kind of crop; air temperature and circulation, oxygen and carbon dioxide contents, and relative humidity of the atmosphere; and disease-inciting organisms. To maintain the fresh vegetable in the living state, it is usually necessary to slow the life processes, though avoiding death of the tissues, which produces gross deterioration and drastic differences in flavor, texture, and appearance.

In the past, the differentiation between cold and cool storages was in terms of the storage of food products with ice or without ice. In broad terms, cool stores operate at air temperatures above -2°C (typically -2 to 10°C) and the cold stores operate below -2°C (typically -15 to -30°C).

Storage under refrigerated conditions is used to slow deterioration of quality in many food products, especially fruits and vegetables. Maintenance of the ideal product temperature and minimization of water loss are both of importance. These are achieved by maintaining uniform conditions (ie, temperature, relative humidity, and air velocity) in the storage environment. Design and operational factors, eg, layout of the store, insulation levels, door protection devices, frequency of door use, air cooling coil and fan designs, associated control system design, air flow patterns, and product stacking arrangements, can all influence the uniformity of environmental conditions and therefore the rate of change of product quality (24).

In the storage operation, the following should be kept in mind: minimizing the exposure of products to ambient temperatures; laying out methods of handling and routes; and never leaving the doors open when personnel or products are passing through them.

Cold storage slows produce respiration and breakdown by enzymes, slows water loss and wilting, slows or stops growth of decay-producing microorganisms, slows the production of ethylene, the natural ripening agent, and buys time for proper marketing. Metabolic activity of fruits and vegetables produces heat. Produce also stores and absorbs heat. The objective of optimum storage conditions is to limit the production, storage, and absorption of heat by produce. Cold storage of produce is refrigerated storage above freezing. Controlled atmospheres, eg, CO_2 or other inert gas around the product, and appropriate humidity control in combination with cold storage gives a longer life of a stored product.

9.4. Controlled Atmosphere Storage (CAS). Since the 1920s a controlled atmosphere has been utilized throughout the world for land-based storage of apples, but its utilization for other fruits and vegetables was limited until the 1980s (25). The history and development of controlled atmosphere storage for apples are well documented in the literature (26).

CAS is used to extend the storage life of seasonal perishable produce when refrigeration alone is not sufficient. This technique can be used for many fruits and vegetables and, historically, has been the principal storage method for the world's apple crop. Apples still remain the preeminent produce stored under CA conditions but, in recent years, it has become an important storage technique for many other commodities.

To store fruit successfully for long periods, the natural ripening of the produce has to be delayed without affecting the eating quality. This is achieved first by reducing the temperature of the fruit to the lowest level possible without causing damage through freezing or chilling. To delay the ripening even further, the atmosphere in the storage room is altered by reducing the oxygen and allowing the CO_2 to increase. The precise level of temperature, oxygen, and CO_2 required to maximize storage life and to minimize storage disorders is extremely variable. This will depend on the type of produce, cultivators, growing conditions, maturity and postharvest treatments. Storage behavior can even vary from farm to farm and from season to season. Recommendations are published regularly by the various national research bodies and preservation consultants who are considered to offer the best advice on the difficult compromise between extending life and minimizing storage disorders in their locality.

The term controlled atmosphere is derived from the fact that the composition of the atmospheric gases in contact with the products is controlled at precise levels during storage or transportation in order to prolong and extend the storage and market life of fresh fruits and vegetables. The amount of fruits and vegetables shipped internationally under a controlled atmosphere has increased drastically $\sim 20\%$ of the total.

Controlled atmosphere technology is a standard technique for the postharvest handling of fruits, vegetables, and stored grains and is one of the main reasons that high quality produce is available throughout the year. This technology is a simple and environmentally safe way to manage postharvest insect and disease problems in cold storage. The use of low oxygen (anoxia) and high carbon dioxide and nitrogen environments simply smother insects. Anoxic environments could be a practical, cost-effective and safe way to kill all life stages of insects and mites that infest greenhouse flower crops. Unfortunately, nearly all information on effects of anoxic environments on insects concerns pests of fruits, vegetables, and grains in storage.

In fact, CA storage does not improve fruit quality, but it can slow down the loss of quality after harvest. Successful CA storage begins by harvesting fruit at its proper maturity. Apples should be cooled rapidly and recommended atmospheric conditions achieved shortly after field heat is removed. The longer it takes to adjust carbon dioxide and oxygen levels, the less effective the duration of storage.

9.5. Refrigerated Transport. Since the 1920s controlled atmospheres have been used throughout the world for land-based storage of apples, but then utilization for other produce and for transportation was limited until the 1980s. During the past decade, the utilization of controlled atmospheres for transport refrigeration was introduced and made this type of transportation more advantageous, owing to the extended storage life of food products. Prompt utilization of this technology has allowed shipment from greater distances and made sea transportation a viable alternative to air freight. Over 95% of international trade in perishable cargoes is accounted for by only seven commodities: meat, fish, dairy produce, deciduous and citrus fruits, bananas, exotic fruits, and vegetables. The rest covers, eg, flowers and plants, pharmaceuticals and medicines, human organs, photographic material, and a variety of industrial commodities.

The modern food distribution system is expected: to deliver foods requiring different storage and transportation temperatures to food stores; to control temperature within a narrow range; to have a rapid temperature recovery after loading and door openings during delivery; to have a safe, quiet system to minimize noise levels and allow night deliveries to food stores; and to have a transport refrigeration system that does not utilize CFCs as refrigerants.

The requirements for the product environment during transportation and distribution are generally the same as for cold storage. But the time of exposure is normally much shorter and technical difficulties in maintaining low temperatures are greater. Also, there is a need for better temperature control in transportation.

In transport by sea, some problems (eg, mainly temperature rise) in maintaining satisfactory conditions are relatively slight and the situation has been improved considerably over the past few years. The types of insulation and the refrigeration unit used are much the same as in any stationary cold store. Suitable ships are now available to satisfy every requirement for any type of refrigerated food.

In transport by land, more difficult problems from a technical and economic standpoint arise. The small individual units of road or rail trucks set narrow limits on the complexity and cost of the cooling equipment. A high degree of reliability is required.

The refrigeration unit fans cause temperature-controlled air to circulate around the inside of the vehicle floor, walls, doors, and roof to remove heat that is conducted from the outside. Some of the air should also flow through and between the cargoes, particularly when carrying fruits and vegetables, in which case heat of respiration may be a significant proportion of the heat load.

On refrigerated semitrailers the compressor is usually driven by a two-speed diesel engine, which also drives the condenser and evaporator fans. Some units also include an electric motor drive as a standby for use in ferries and where noise regulations are in force. A thermostat is mounted on the front casing of the unit with the sensor placed in the return air stream. A dial thermometer is usually fitted in a prominent position where it can be seen by the driver, with the sensor placed adjacent to the thermostat sensor.

For land transport, the refrigerated semitrailer is the most popular vehicle. Rigid vehicles are used for local deliveries and short-distance journeys. For marine transport, two types of container are more common, one having an built-in refrigeration unit similar to the refrigerated semitrailer and the other having two circular apertures on the front wall through which refrigerated air may be ducted. The second one is known as a porthole unit and may be refrigerated in land or road transport by a detachable refrigeration unit using a conventional vapor compression system, liquid nitrogen, or dry ice.

10. Conclusions

This article has dealt with the technical aspects of refrigerants, refrigeration systems and applications, and food cooling and refrigeration. It covers the refrigerants; alternative refrigerants; refrigeration system components, and auxiliary equipment and their technical and operational aspects; refrigeration cycles/ systems; thermoelectric refrigeration; thermoacoustic refrigeration; solar refrigeration, etc; food cooling and freezing systems; cool and cold storage; control atmosphere; as well as refrigerant transport. Some practical details are also provided for better understanding the refrigeration cycles–systems and their applications.

BIBLIOGRAPHY

“Refrigeration” in *ECT* 2nd ed., Vol. 17, pp. 295–327, by J. R. Chamberlain and R. A. Dorwart, York Division, Borg-Warner Corp.; in *ECT* 3rd ed., Vol. 20, pp. 78–107, by K. W. Cooper and K. E. Hickman, York Division, Borg-Warner Corp.; in *ECT* 4th ed., Vol. 21, pp. 128–149, by H. W. Sibley, Carrier Corp.; “Refrigeration” in *ECT* (online), posting date: December 4, 2000, by H. W. Sibley, Carrier Corp.

CITED PUBLICATIONS

1. I. Dincer, *Refrigeration Systems and Applications*, John Wiley & Sons, Inc., New York, 2003.
2. F. S. Rowland, *Annu. Rev. Phys. Chem.* **42**, 731 (1991).
3. ASHRAE (2004). *Handbook of Refrigeration*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Ga.
4. O. Badr, S. D. Probert, and X. O’Callaghan, *Appl. Energy* **37**, 247 (1990).
5. G. Lorentzen, Application of natural refrigerants, *Proceedings of the Meeting of I.I.R. Commission B1/2*, 12–14 May, Ghent, Belgium, 1993, pp. 55–64.
6. S. F. Pearson, *Refrigeration Air Conditioning*, July, 21–23 (1991).
7. X. Anon, *Refrigeration Air Conditioning*, July, 32–33 (1991).
8. R. P. Wayne, *Chemistry of Atmospheres*, 2nd ed., Oxford University Press, Oxford, 1991.
9. R. D. Heap, *Heat Pumps*, E. & F.N. Spon Ltd., a Halsted Press (Wiley), New York, 1979.
10. R. W. Haywood, *Analysis of Engineering Cycles*, 3rd ed., Pergamon, Oxford, 1980.

11. S. Aphornratana, S. Chungpaibulpatana, and P. Srikhirin, *Int. J. Energy Res.* **25**, 397 (2001).
12. S. Godfrey, *Electronics Cooling*, September issue 4, 1–6 (1996).
13. S. L. Garrett and S. Backhaus, *Am. Sci.*, November–December issue. Available at http://www.sigmaxi.org/amsci/articles/00articles/garrettbib.html.
14. I. Dincer, *Determination of the Effective Process Parameters and Heat Transfer Characteristics of Several Food Products during Cooling*, Ph.D. dissertation, Faculty of Mechanical Engineering, Istanbul Technical University, Istanbul, Turkey, 1993.
15. I. Dincer, *J. Food Eng.* **26**, 243 (1995).
16. I. Dincer, *Int. J. Energy Res.* **19**, 95 (1995).
17. I. Dincer, *Appl. Energy* **50**, 269 (1995).
18. I. Dincer, *Appl. Energy* **51**(2), 125 (1995).
19. I. Dincer, *Int. J. Energy Res.* **19**(9), 791 (1995).
20. I. Dincer, *Appl. Energy* **50**(3), 269 (1995).
21. USDA Tropical Products Transport Handbook, The U.S. Department of Agriculture (USDA), Washington, D.C., 2001.
22. J. M. Jay, *Modern Food Microbiology*, 5th ed., Chapman & Hall, New York, 1996.
23. I. Dincer, *Heat Transfer in Food Cooling Applications*, Taylor & Francis, Washington, D.C., 1997.
24. N. D. Amos and co-workers, A survey of air velocity, temperature and relative humidity in a large horticultural coolstore, *Proceedings of the International Meeting on Cold Chain Refrigeration Equipment by Design*, 15–18 November, Palmerston, New Zealand, 1993, pp. 414–422.
25. A. C. Stera, Developments in transportation of chilled produce by sea and air, *Proceedings of the International Meeting on Cold Chain Refrigeration Equipment by Design*, 15–18 November, Palmerston, New Zealand, 1993, pp. 46–67.
26. D. H. Dewey, Controlled atmosphere storage of fruits and vegetables, *Developments in Food Preservation-2*, S. Thorne, ed., Applied Science Publishers, London, Chapt. 1, 1983, pp. 1–24.

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Table 1. **Comparison of Quick Freezing and Slow Freezing**

Quick freezing	Slow freezing
small ice crystals formed	large ice crystals formed
blocks or suppresses	breakdown of metabolic rapport
brief exposure to concentration of adverse constituents	longer exposure to adverse or injurious factors
no adaptation to low temperatures	gradual adaptation
thermal shock (too brutal a transition)	no shock effect
no protective effect	accumulation of concentrated solutes with beneficial effects
microorganisms frozen into crystals	
avoiding internal metabolic imbalance	

Table 2. **Freezing Temperatures of Various Food Commodities**[a]

Food commodities	Freezing temperature range, °C
fruits (eg, strawberries, figs)	−15 to −20
vegetables (eg, beans, peas, peppers)	−10 to −20
home foods (eg, ready-to-eat foods)	−18 to −40
meats (eg, carcass beef, chicken)	−20 to −35
fish (eg, shrimp, small and large fish, tuna)	−20 to −50

[a] See Ref. 1.

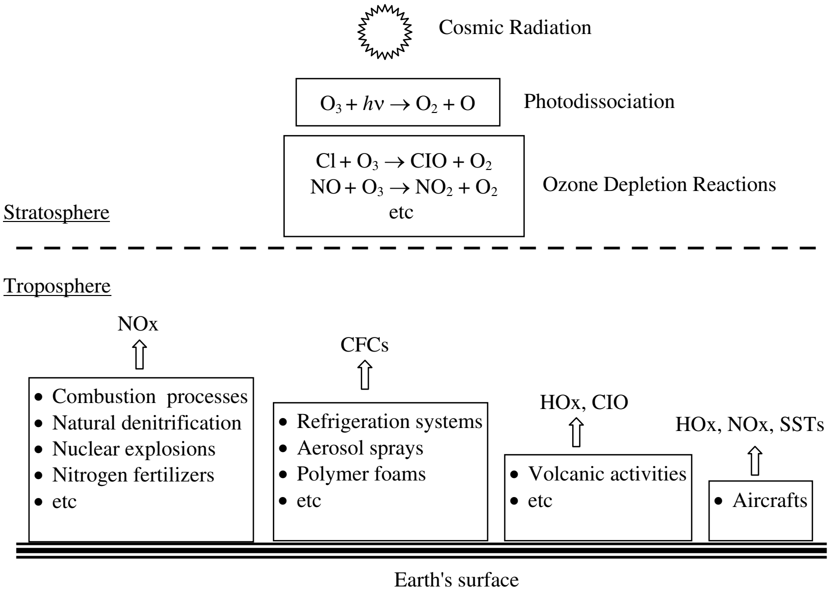


Fig. 1. A schematic representation of stratospheric ozone depletion.

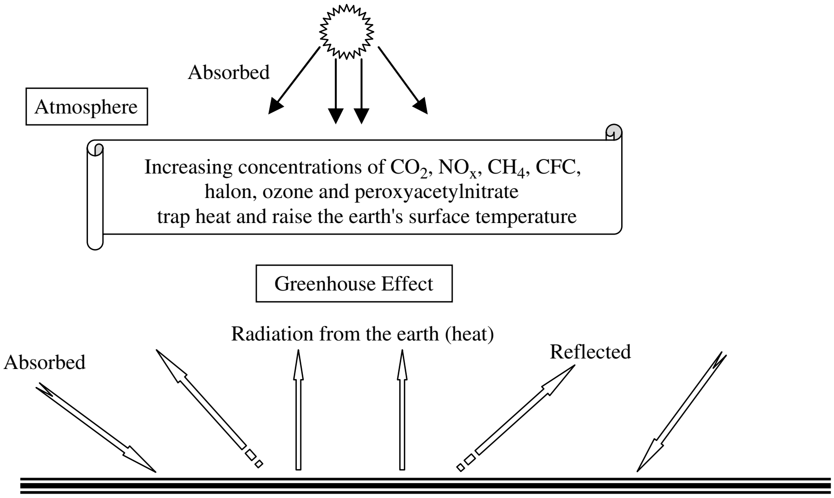


Fig. 2. A schematic representation of the Greenhouse effect.

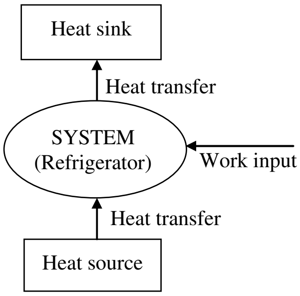


Fig. 3. A thermodynamic system acting as a refrigerator.

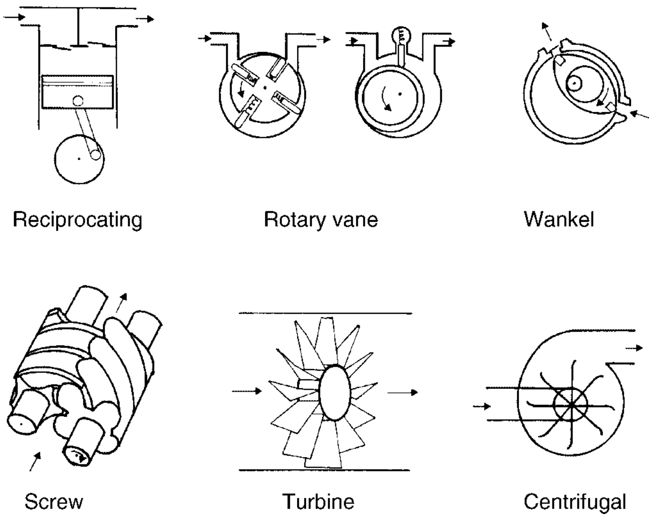


Fig. 4. Compressor types (9).

Fig. 5. Various water-cooled condensers. (Courtesy of Standard Refrigeration Company.)

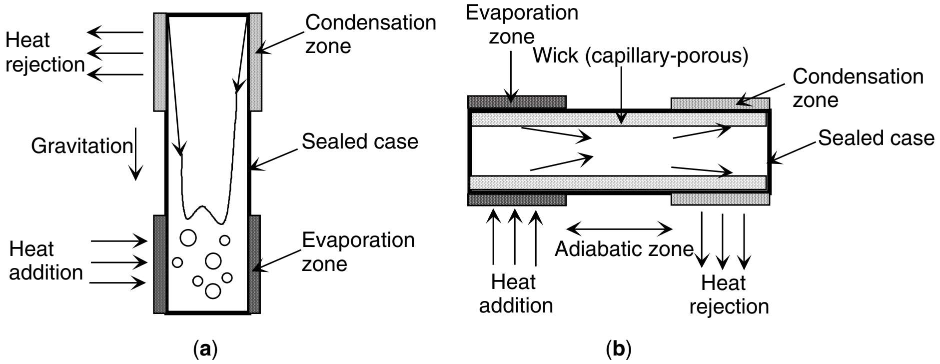


Fig. 6. Two basic heat pipe configurations: (**a**) thermosiphon and (**b**) capillary driven.

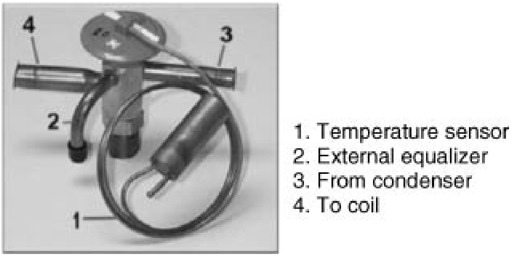


Fig. 7. An electronic expansion valve. (Courtesy of Danfoss A/S.)

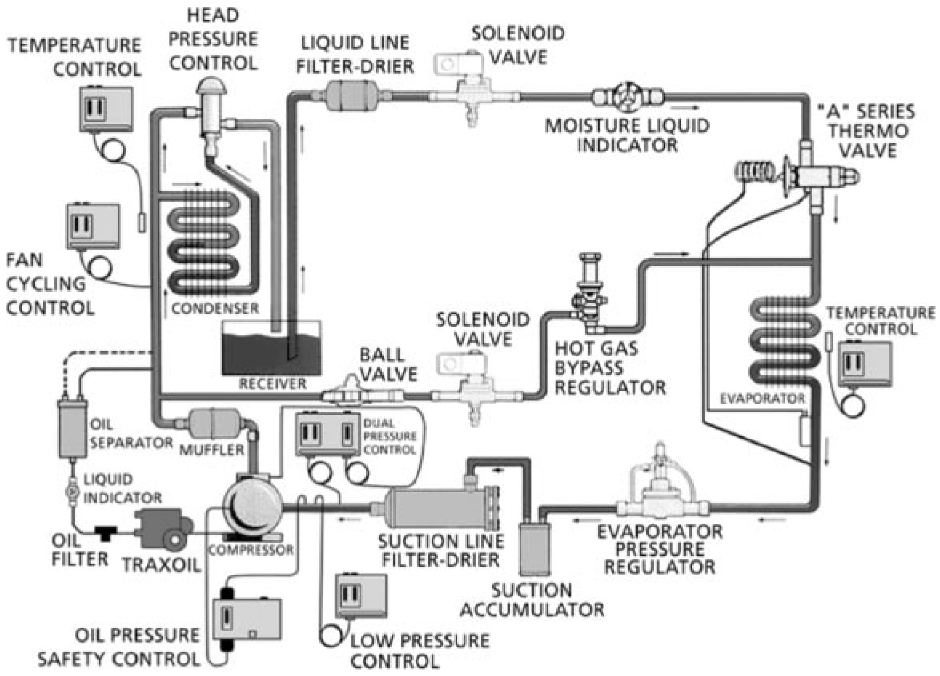


Fig. 8. A practical vapor compression refrigeration system with all control devices. (Courtesy of ALCO Controls.)

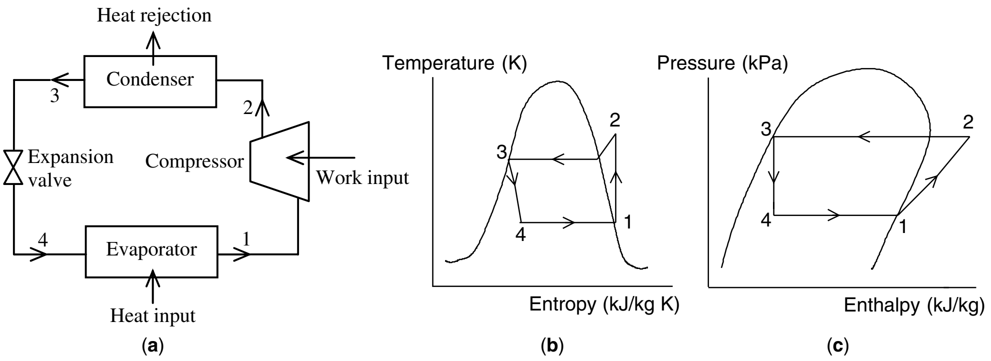
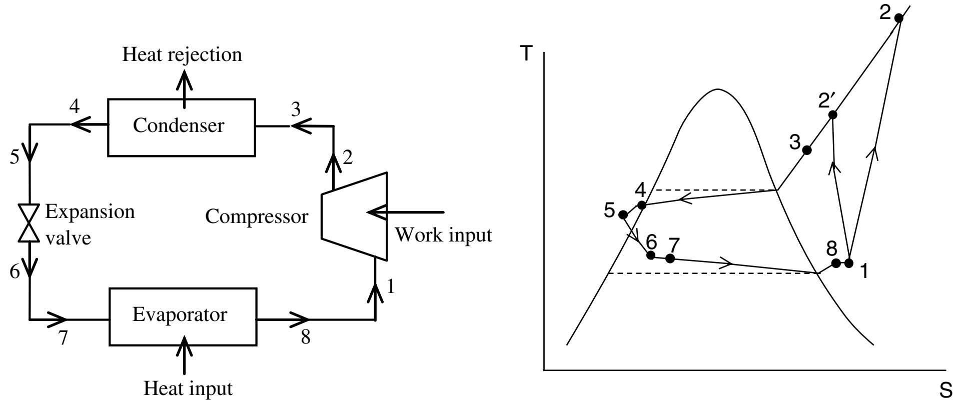


Fig. 9. (**a**) A basic vapor–compression refrigeration system, (**b**) its T–s diagram, and (**c**) its log P–h diagram.



(**a**) (**b**)

Fig. 10. (**a**) An actual vapor–compression refrigeration system and (**b**) its T–s diagram.

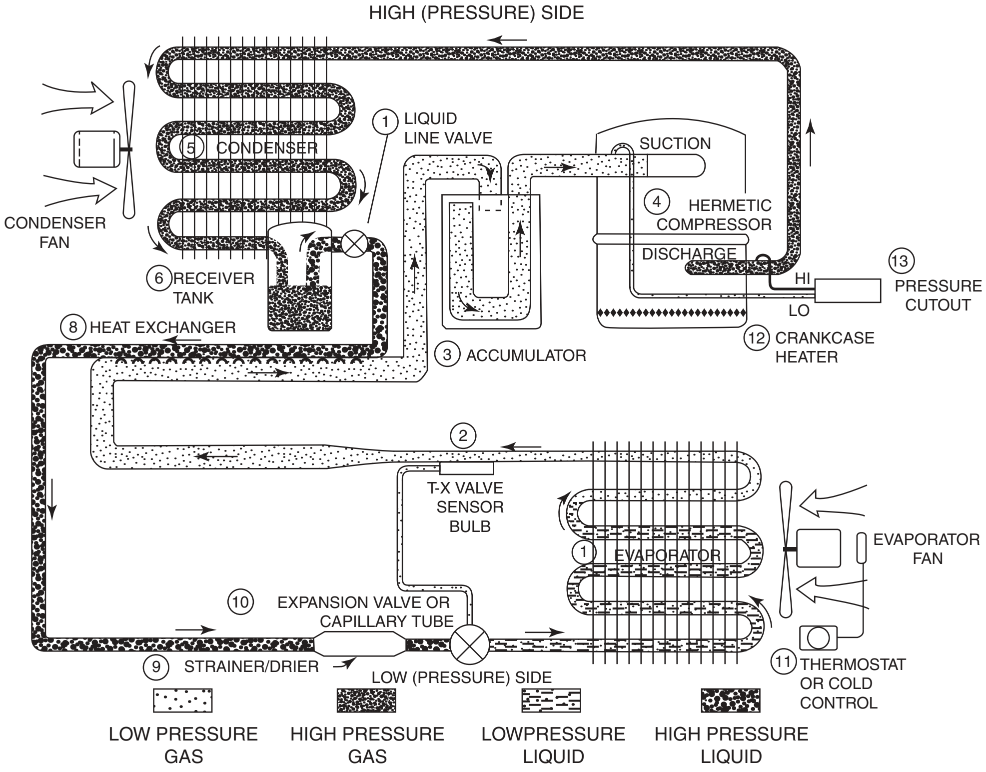


Fig. 11. A typical commercial refrigerating unit. 1. Evaporator inlet. 2. Evaporator outlet. 3. Accumulator. 4. Compressor. 5. Condenser inlet. 6. Condenser outlet. 7. Receiver outlet. 8. Heat exchanger. 9. Liquid line strainer/drier. 10. Expansion valve. 11. Thermostat. 12. Compressor crankcase heater. 13. High and low pressure cutout. (Courtesy of Tecumseh Products Co.)

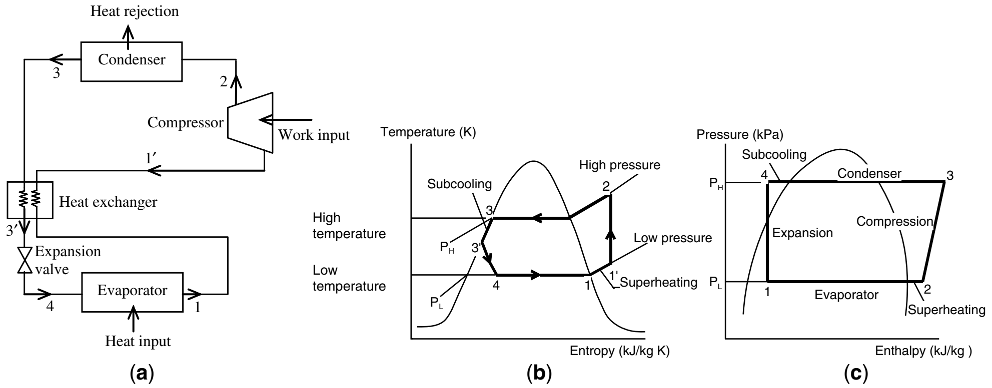


Fig. 12. (**a**) A vapor–compression refrigeration system with a heat exchanger for superheating and subcooling, (**b**) its T–s diagram, and (**c**) its log P–h diagram.

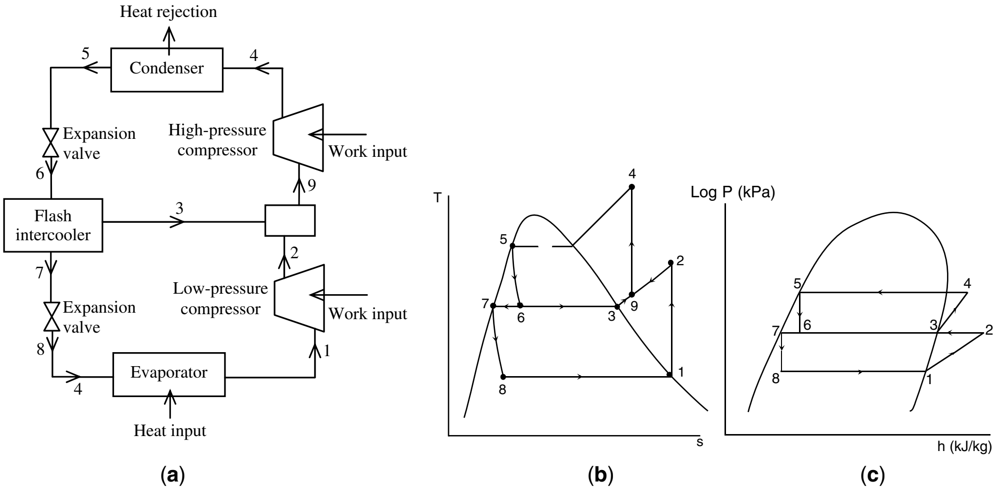


Fig. 13. (**a**) A two-stage vapor–compression refrigeration system, (**b**) its T–s diagram, and (**c**) its log P–h diagram.

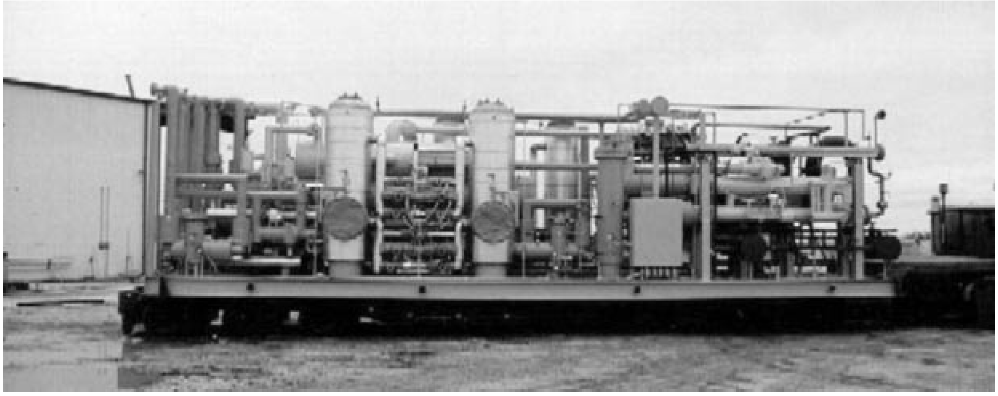


Fig. 14. A cascade refrigeration system utilizing CO_2 as low pressure stage refrigerant and ammonia as the high pressure stage refrigerant (operating at about −50°C), skid for a 100 ton/day CO_2 liquefaction plant. (Courtesy of Salof Refrigeration Co., Inc.)

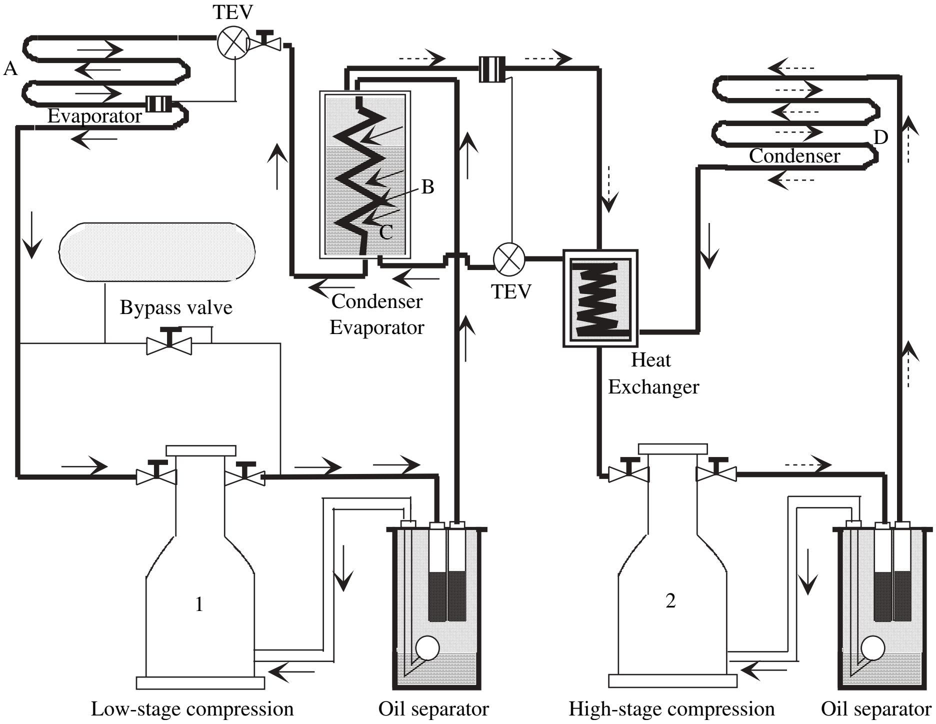


Fig. 15. A practical two-stage cascade refrigeration system.

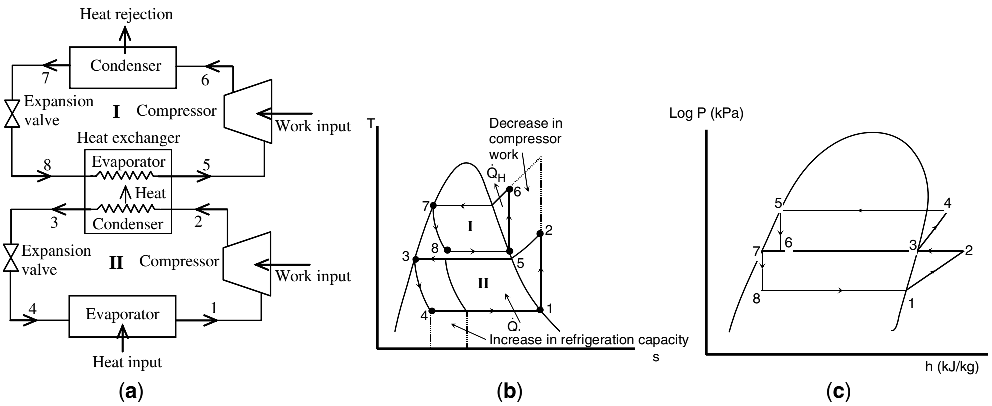


Fig. 16. (**a**) Schematic of a two-stage (binary) cascade refrigeration system, (**b**) its T–s diagram, and (**c**) its log P–h diagram.

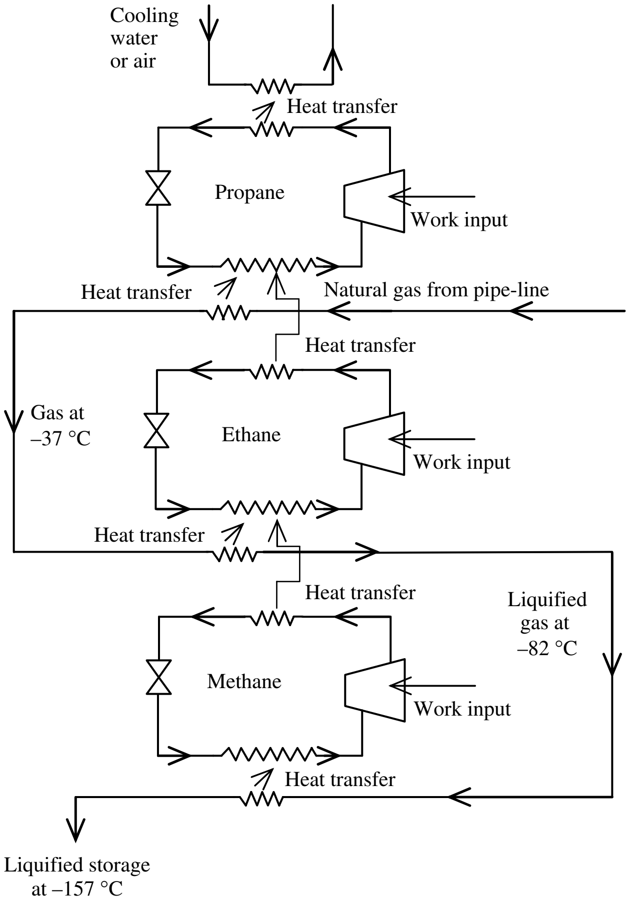


Fig. 17. A three-stage (ternary) cascade vapor–compression refrigeration system.

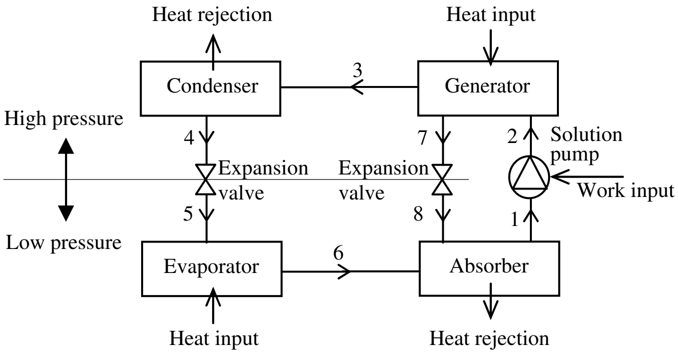
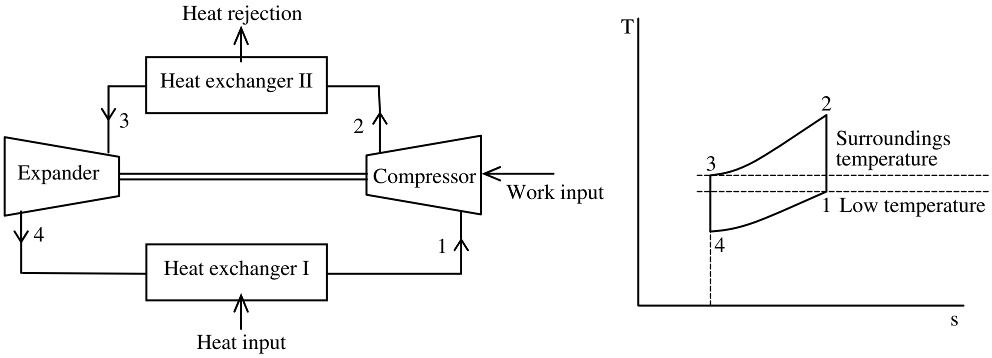
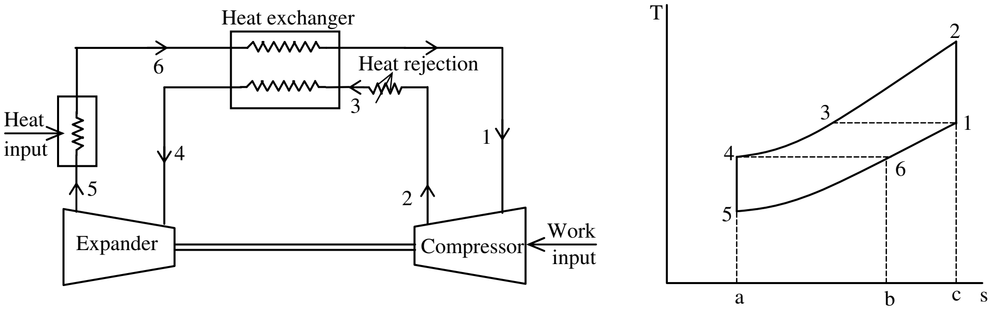


Fig. 18. A basic absorption refrigeration system.



(**a**) (**b**)

Fig. 19. (**a**) A basic air-standard refrigeration cycle and (**b**) its T–s diagram.



(**a**) (**b**)

Fig. 20. (**a**) An air-standard refrigeration cycle using a heat exchanger and (**b**) its T–s diagram.

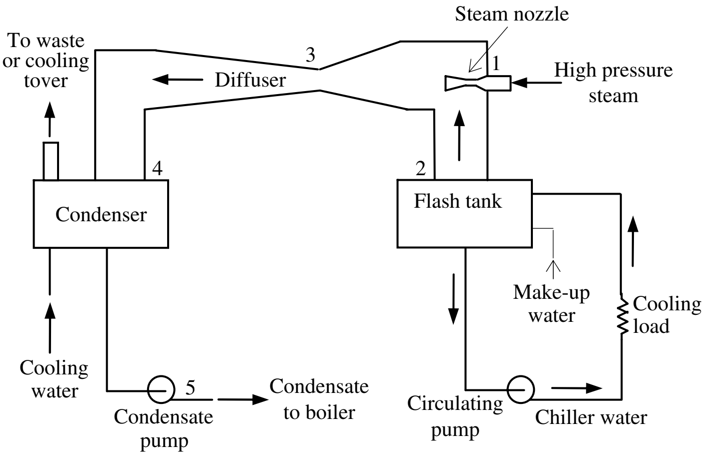


Fig. 21. A steam jet refrigeration system.

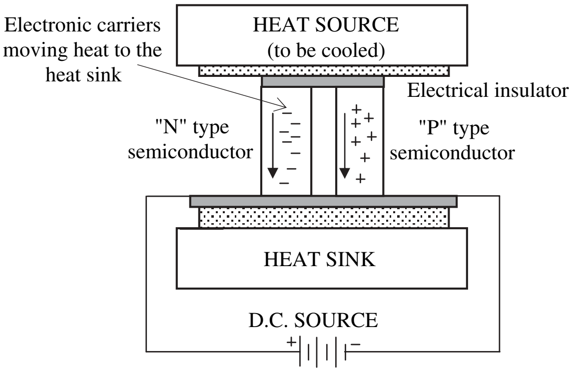


Fig. 22. Cross-sectional view of a typical thermoelectric cooler. (Courtesy of Melcor Corporation.)

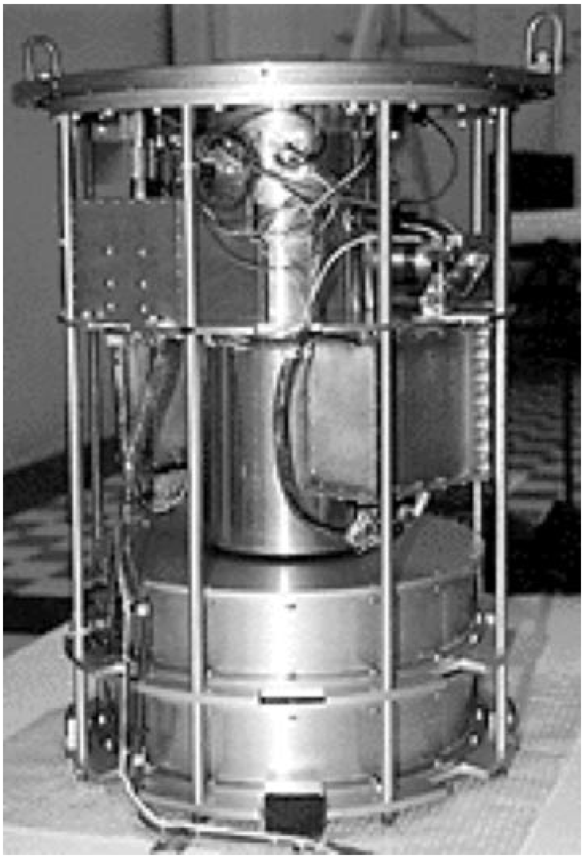


Fig. 23. A thermoacoustic refrigerator. (Courtesy of Pennsylvania State University Applied Research Laboratory.)