MODULE

13

Refrigeration systems

In this module, we will be covering **refrigeration systems**. They are employed in a variety of system types in different fields, from civil to industrial applications. First, we will expand upon the general concepts, along with classification criteria, then we will analyze the representative cycles on different work planes and, lastly, how to dimension the systems themselves. Since a thermal cycle for refrigeration systems moves counterclockwise, it is defined **reverse cycle** and can be used both to provide cold and heat, according to two quite similar plant designs, the **refrigeration cycle** and the **heat pump**, that will be analyzed in detail.

PREREQUISITES

- Knowing the definitions of the thermodynamic quantities, in particular those of temperature and heat
- Understanding combustion processes
- Understanding thermodynamic transformations

OBJECTIVES

- Knowing and distinguishing between the different types of plant design applications
- Knowing the properties of cooling fluids
- Knowing how to perform an energy balance
- Knowing how to size the physical parameters of the machines
- Knowing how to represent on the work planes the ideal and real cycles
- Knowing how to assess the performance of the plant

UNIT 23

Reverse cycle systems

23.1 Description and field of application

Refrigeration systems, made up by refrigeration machines, are very complex devices whose function is performing the reverse-Rankine cycle; in fact, by using the mechanical energy, they make it possible to exchange heat between a cold and a hot source. The purpose is, precisely, to subtract heat from the cold source and then move it to the hot source. Currently, it common to refer to this as “production of cold”. This expression is, however, technically wrong, since it is known from the fundamental principles of thermodynamics that heat can be transferred from a warmer to a colder body. Now, this is not possible with the common fluids used for all other installations seen so far, but if a fluid is used which, even at low temperatures, represents the cold source, then it is possible for the heat to move form a cold body to an even colder one. From this the expression **subtract heat from a cold source** derives. The fluids that can remain in the liquid state at very low temperatures are those defined as **refrigerants**, which are to have very low freezing points.

This type of installations finds application in various civil engineering and industrial fields of application; in the first case, to cool the air within a confined space in order to maintain thermal comfort (see air conditioning systems) or to cool the air in the rooms where perishable food products are stored (see cold stores or refrigerating rooms for storing foodstuffs); in the second case, for the production of ice (see ice factories) or lyophilization, i.e. drying at a low temperature or vacuum-drying delicate substances (see pharmaceutical industries or applications in biology).

23.2 The reverse cycle

To make what previously described possible, the system that carries out this operation must consist of a motor, an machine, and two heat exchangers, as shown in Figure 23.1.

The fluid, moving counterclockwise in the plant, performs the following transformations:

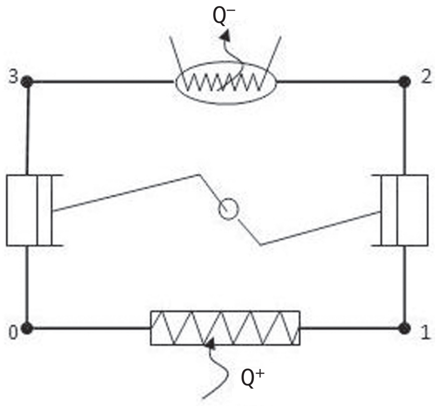
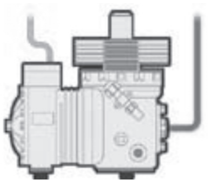


Figure 23.1

- **1-2 adiabatic compression (1)**, performed by a compressor (or machine) that takes the fluid from temperature T_1 to temperature T_2 in the physical state 2; this is the phase in which mechanical work is used;
- **2-3 isothermal condensation (2)**, carried out by means of a condenser, this is the phase when the fluid transfers heat to the hot source;

- **3-0 adiabatic expansion** carried out by a turbine (or motor) that takes the fluid to the state 0 of saturated steam at a temperature $T_1 < T_2$; this is the phase when mechanical work is produced that is used in the turbine;
- **0-1 isothermal expansion (3)** performed by means of an evaporator or vaporizer; the fluid is vaporized to condition 1; this is the phase when the amount Q_2 of heat is absorbed from the cold source.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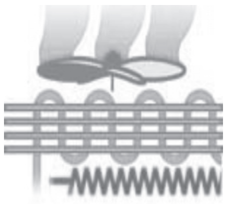
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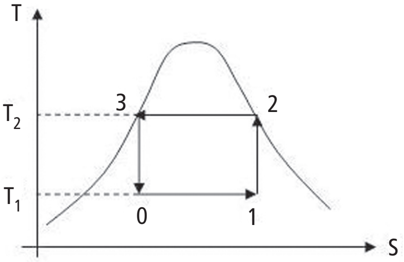
The representation of the diagram of the plant on a *T-S* temperature plane is the reversed Carnot cycle, consisting of two adiabatic transformations (in the machines) and two isothermal transformations (in the heat exchangers), as shown in Figure 23.2.



The diagram of the plant of Figure 23.1, a diagram that is purely ideal, has, in practice, a drawback for the turbine, because the fluid is in the moist saturated steam condition, and therefore there would be two phases in the machine: liquid and vapor.

Motors capable of operating with fluids in these conditions are not suitable because of the technical difficulties arising in the implementation phase; therefore, the idea arose to replace the motor with a **valve**, which is an extremely simple mechanism, since it involves a *isenthalpic transformation*, i.e. at a constant enthalpy, and not adiabatic.

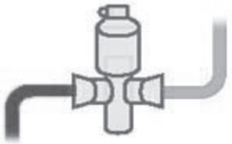

Valve

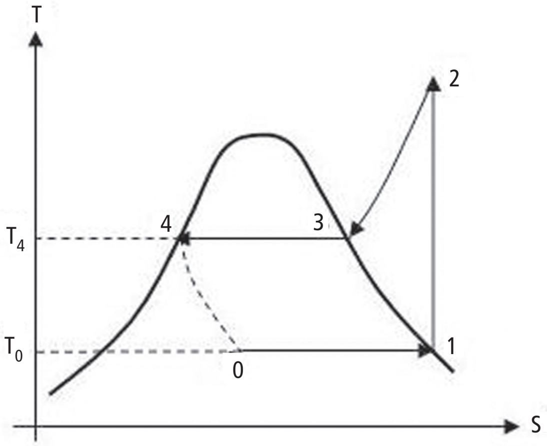
Figure 23.2

The isenthalpic transformation (4-0) of Figure 23.3 is an irreversible adiabatic with dissipation through heat of the kinetic energy during the expansion phase, with a consequent variation of the intrinsic energy of the fluid so that, however, the total thermal content of the fluid between inlet and outlet of the valve can be thought of as being constant.

Not only does replacing the turbine with the expansion valve entail a variation in the diagram of the plant, but also, especially, in the representative cycle, as shown in Figure 23.4.

The presence of the valve in the plant has negative consequences linked both to the reduction of the area of the cycle, and therefore a decrease of the cooling effect, and to the annulment of the positive work since the enthalpy values are equal. It is worth mentioning, however, that these effects are negligible compared to the practical advantages of using a valve. To compensate for the reduction in the cooling effect (*understood as the amount of heat absorbed in the evaporator from the refrigerant fluid*), together with the fact that the compressor as well would have to work with a fluid that is, at the same time, both in the liquid and in the vapor phase, with consequent difficulty of adjustment, this step is usually carried out completely in the vapor stage, prolonging the evaporation up to the point on the upper limit curve of the bell (see Figure 23.5). Therefore, the real operation cycle of a refrigeration system is that shown in Figure 23.3.

Figure 23.3



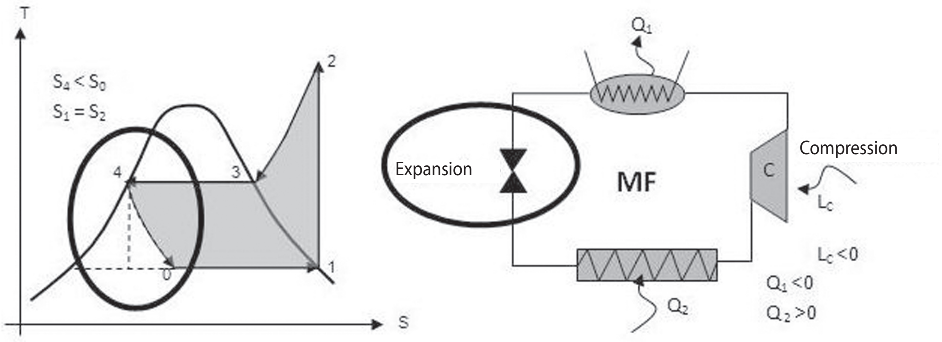


Figure 23.4

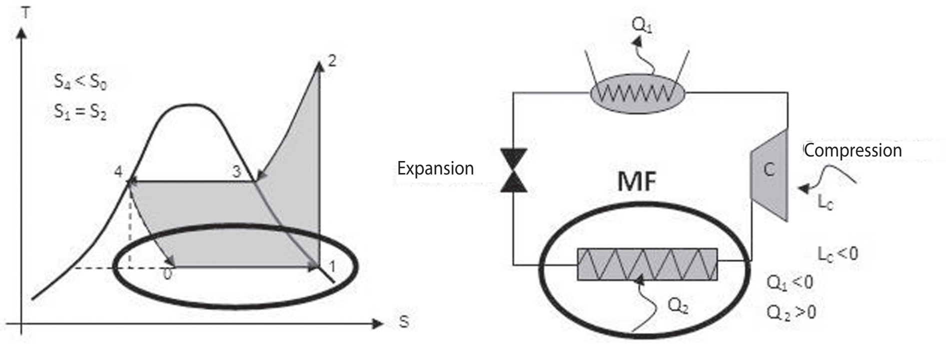
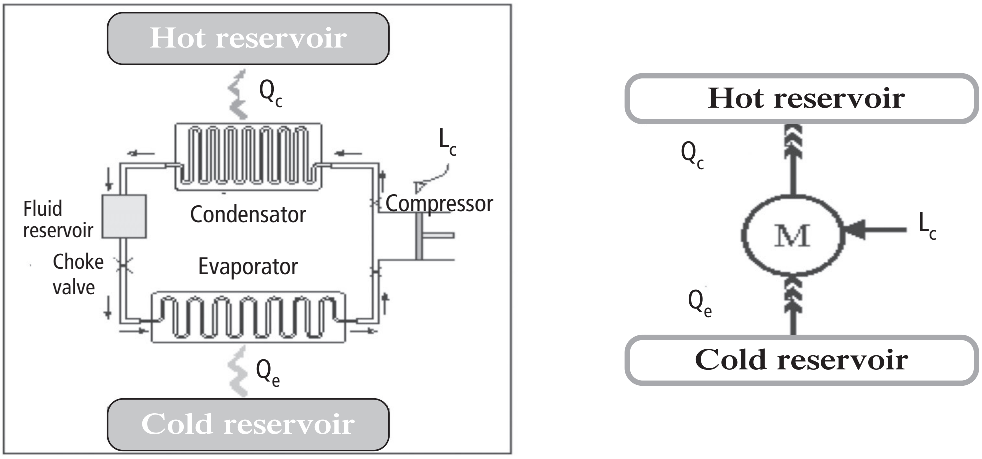


Figure 23.5



Summarizing diagram of the refrigerating machine

23.3 COP and EER - Potentialities

The analysis of the ideal cycle starts from its energy balance that, in accordance with the first principle of thermodynamics, evaluates the work spent and the heat being exchanged:

$$L = Q_1 - Q_2 \tag{23.1}$$

where:

- L work spent per kg of circulating fluid
- Q_1 heat transferred to the hot source through the condenser
- Q_2 heat absorbed from the cold source through the evaporator

Knowing from thermodynamics that an adiabatic transformation is also isentropic, a condition laid down by the formula:

$$Q = T\,\Delta S = T\,(S_f - S_i) \tag{23.2}$$

we obtain, replacing in (23.2):

$$L = T_2\,(S_2 - S_3) - T_1\,(S_1 - S_0) = (T_2 - T_1)\,\Delta S$$

the theoretical efficiency of the cycle is:

$$\eta = \frac{Q_2}{L} = \frac{T_1\,\Delta S}{(T_2 - T_1)\cdot \Delta S} = \frac{T_1}{T_2 - T_1}$$

It is clear that $\eta > 1$ and that, the greater this value, the smaller the thermal jump $(T_2 - T_1)$, i.e. the closer together the two isotherms, upper and lower, are.

Talking about efficiency in the strict sense of the term seems to be counterproductive, because it has always been said that no thermal machine may exceed 100% yield and then $\eta > 1$; since the cycle is reversed with respect to the traditional ones, it is more meaningful to talk about **efficiency** ε or, better, of **EER** (***Energy Efficiency Ratio***) understood as the **efficiency of energy transformation,** from the meaning of the English term it is clear that it refers to the relation between two thermal powers, that of the heat absorbed from the evaporator and the power absorbed by the compressor, therefore:

$$EER = \frac{Q_{evap}}{P_{comp}} \tag{23.3}$$

Considering the thermal powers in energy terms as the enthalpy difference between the end points of the transformations it follows that:

$$Q_{\text{evap}} = h_1 - h_0 \qquad P_{\text{comp}} = h_2 - h_1$$

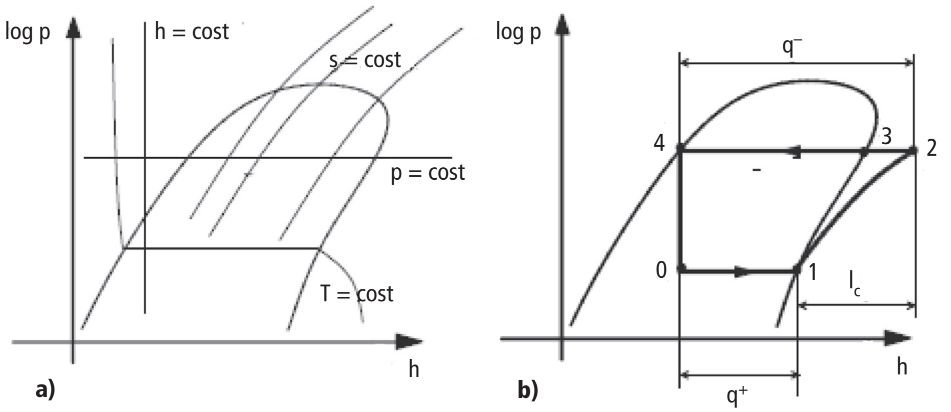
Replacing in (23.3), we obtain:

$$EER = \frac{h_1 - h_0}{h_2 - h_1} \tag{23.4}$$

Since both the efficiency of the cycle and the refrigeration effect are evaluated in terms of enthalpy jumps, it is more practical to represent the cycle on an enthalpic plane, whose cartesian axes are the enthalpy (H), on the abscissa, and the pressure in logarithmic scale ($\log p$) in ordinate, so as to have the immediate reading of the values. The enthalpic plane, as all the other work planes, highlights the physical state of the fluid separated by a bell, which represents the ends of the liquid and vapor fields.

The real cycle on the enthalpic plane is shown in Figure 23.6.

Figure 23.6



Substantially, the concept of **COP** (**Coefficient of Performance**), meant as the **coefficient of performance**, does not vary compared with EER; however, since it refers to systems that use heat pumps for supplying heat, it will be analyzed in detail in paragraph 23.5.

23.4 Refrigerating fluids

From a theoretical point of view, in plants operating with steam compression it would be possible to use any fluid having a critical temperature higher than the ambient temperature.

In reality, the fluids that are being used are those whose characteristics make installations adequate from the construction and operational point of view as well.

Some characteristic properties of these fluids are:

- **heat of vaporization**: a high value decreases the amount of fluid circulating in the plant, the subtracted heat being the same; this characteristic makes it, in practice, unusable for very small systems because of the difficulties that are to be expected in implementing control devices with very narrow passages;
- **specific volume of saturated steam**: property that has a strong influence on the size of the compressor;
- **vaporization pressure**: it is advisable this value were slightly higher than the atmospheric pressure so as to prevent the air from entering into the circuit of the refrigerant through any passage points;
- **critical temperature**: this value should be very high relatively to the ambient temperature so as to guarantee a regular operation when the cold fluid of the condensator is water or air at a high temperature
- **other characteristics**:
  - *they are not to be poisonous*: when this is not possible, refrigerants are to have a peculiar odor or contain a tracer fluid, so that any leaks can be identified quickly;
  - *they are to be neither explosive nor flammable*: when this condition cannot be met the precautions prescribed by current safety regulations must be taken;
  - *they are to be chemically stable* at the temperatures and pressures generated in normal conditions in the system;

- *they are not to be corrosive* and must not corrode, when in the liquid or gaseous state, the materials the various apparatuses are made of;
- *they are not to decompose the lubricating oils*;
- *they are to be easy to find*;
- *they are to be not too expensive*.

However, it is well known that, in practice, different refrigerants are used depending on the requirements and applications. The most important have been ammonia and the Freon class.

Ammonia (NH_3)

Its advantage is that it is very affordable, but it has serious drawbacks from the hygienic-environmental point of view:

- it is irritating to the respiratory system;
- it may become explosive when mixed with oxygen (O_2).

Ammonia is very common in large installations. In small plants it can be used only if the refrigeration machines are external to the house.

In this type of system ammonia is used for heating and/or cooling the water that is subsequently entered into the environment through tubes. The disadvantage of this solution is that it has a large expenditure of energy, but it is not possible to let ammonia flow directly into the tubes because of its danger.

Freon

Lately, to solve the previously mentioned problem, ammonia has been replaced with the family of chlorofluorocarbons (CFC), commercially called Freon (the most famous is the R12) made by the DuPont company. Freon are organic compounds combined with atoms of chlorine and fluorine.

Freon cannot be considered 100% harmless but, unlike ammonia, these substances are not flammable, do not explode and do not irritate the respiratory tract, but their chemical stability makes them indestructible and when they are released in the environment they do not degrade, but remain the same. Therefore, they accumulate in the environment, causing serious damage.

The main **sources of freon** in the environment are:

- defective refrigerating machines ;
- spray cans containing CFCs;
- refrigerators for domestic use when they are scrapped (when industrial refrigeration machine are scrapped, freon is recovered and reused).

The main **environmental damages** caused by freon are:

- the hole in the ozone layer;
- the greenhouse effect.

The hole in the ozone layer. Ozone (O_3) is a gas that is found in the atmosphere, and which is responsible for reducing the intensity of the ultraviolet radiation emanating from the sun. This substance is made up of three atoms of oxygen and is created when a collision occurs between an oxygen atom and an oxygen molecule; the reaction is catalytic and the atom binds to the molecule with a distinct, fairly weak bond called “dative”.

The main function of the ozone is, as previously said, to absorb ultraviolet radiation from the sun; therefore, it acts as a protective filter without which life on Earth would not be possible.

Freon, and in general all CFCs, whose presence in the environment has become increasingly more significant and worrying since the 70s, break the weak bond of ozone, decreasing the amount of this gas and consequently its ability to filter UV radiation. The result is a real risk to life on our planet.

The serious phenomenon of the depletion of the ozone layer was acknowledged in 1985: some scientists noticed that the ozone layer above the antarctic icecap had decreased by about 40% and this depletion of molecules of O_3 showed, and is still showing today, the tendency to intensify.

Since the mid-nineties, CFC production was forbidden; today, other gases derived from CFC are used, including hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which are less dangerous than CFC but not entirely harmless.

The greenhouse effect. The greenhouse effect is a phenomenon linked to thermal irradiation.

Earth receives energy from the sun in the form of electromagnetic radiation (“short waves” with a relatively short wavelength λ, belonging to the ultraviolet spectrum), absorbs it, and transforms it into heat (with a longer λ wavelenght, falling in the infrared band), reflecting it.

Due to its wavelength, the radiation from the sun can easily penetrate the atmosphere without being significantly absorbed.

The atmosphere is, in fact, constituted by gases that do not absorb, if not in small amounts, short wavelengths, while they stop long wavelengths. When this radiation arrives on the surface of the Earth (about 50% of the total energy coming from the sun), it is absorbed by the soil and is gradually released into the environment in the form of heat, warming the Earth from the surface up.

In this situation, the atmosphere behaves as if it were a greenhouse: it lets the solar radiation in but does not let the thermal radiation reflected from the ground escape, trapping heat. It is precisely because of this similarity that the term *greenhouse effect* was coined.

The gases that influence the most the greenhouse effect are the water vapor and the carbon dioxide present in the atmosphere. With industrialization, the presence in the environment of carbon dioxide has considerably increased. The amount of pollutant gases such as carbon dioxide, methane, sulfur dioxides, coal etc, is still on the rise today.

All these substances are doing nothing but increasing the heat-trapping effect of the atmosphere, causing a further rise in the average temperature on Earth, with consequent rise in sea level due to the melting of the polar ice caps.

As a phenomenon, this can be considered to be less dangerous than the hole in the ozone layer. The Earth has repeatedly experienced these cyclic variations of the climate; in fact, the intense volcanic activity of the early age of our planet caused a considerable rise in its temperature. Since the last ice age, the Earth’s temperature has constantly risen; the only problem, however, is that the introduction of pollutants gases due to human activities has accelerated this phenomenon. In about 10,000 years there will be a new ice age.

The properties of some refrigerants are reported in Table 23.1, while in the appendix the table with the fields of application of refrigerants can be found.

Table 23.1 • Properties of refrigerants

	Type		Chemical formula	Saturation pressure (bar)		Specific volume (m³/kg)	Latent vaporization heat (kJ/kg)	Volumetric refr. Prod. (kJ/m³)	ODP*	WP
				–10 °C	25 °C	–10 °C	1 bar	–10-25 °C		
Natural	Water vapor (R718)		H_2O		0,0317		2257		0	0
	Ammonia (R717) NH^3		^{2,899}	10,00 0,	419	1369	2700	0	<1	
	Carbon dioxide (R744)		CO_2							1
	Propane (R290)		C_3H_8							3
	Hydrocarbons (in general)		-							
Synthetic	CFC (chloro-fluorocarbon)	R11	$CFCl_3$	0,257	1,064	0,612	182	267	1	4000
		R12	CF_2Cl_2	2.193	6,517	0,077	162	1608	0,9-1	8500
		R13	CF_3Cl	15,202	35,5	0,010	150		?	?
	HCFC (Hydro-chloro-fluorocarbon)	R22	CHF_2Cl	3,545	1,438	0,065	234	2623	0,04 – 0,06	1700
		R123	CHF_3CCl_2	0,204	0,913	0,690	170	215	0,01 – 0,02	93
	HFC (Hydro-fluorocarbon)	R407C	Mixture							1500
		R134a	$C_2H_2F_4$	2,005	6,655	0,100	217	1589	0	1300

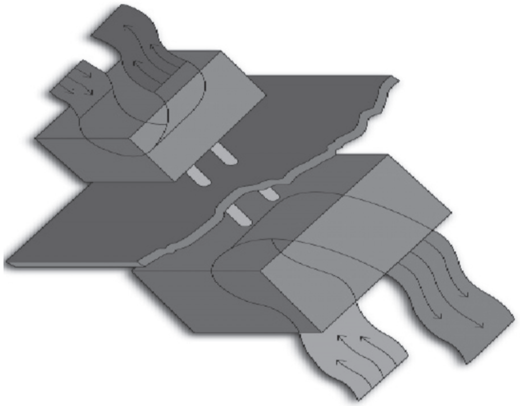
* The ODP (Ozone Depletion Potential) is conventionally expressed with reference to the mass of the refrigerant R11.

23.5 Heat pump

The **heat pump** is a device that allows to heat the air inside a room (which has a higher temperature) by cooling the external air (which has a lower temperature) (Figure 23.7).

As far as its working principle is concerned, it behaves like the refrigeration machines that transfer heat from a source at low temperature to a source at a higher temperature by using external work.

Figure 23.7



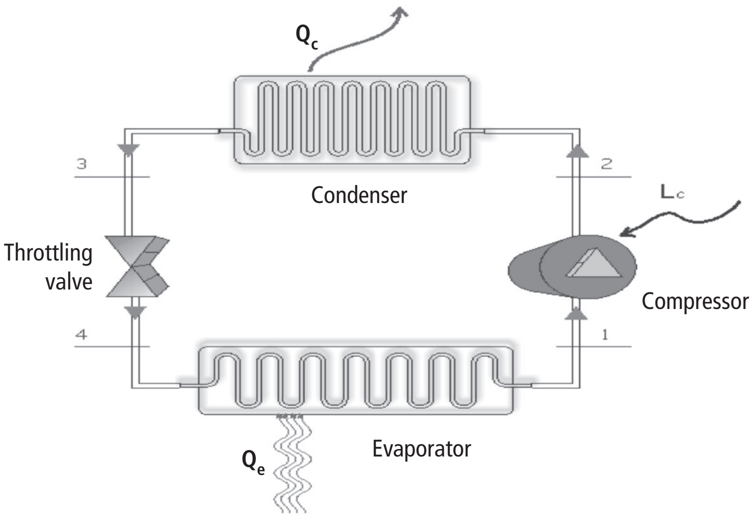


Figure 23.8

The heat pump owes its name to the fact that it takes heat from a lower to a higher temperature level, by reversing the natural flow of heat that, in nature, as known, flows from a higher level (temperature) to a lower one. It consists of a closed circuit (Figure 23.8) wherein a refrigerant fluid flows that, depending on its temperature and pressure conditions can be either in the liquid or gaseous state.

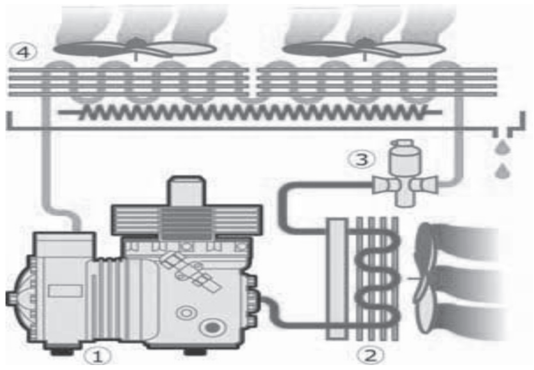
The closed circuit is made up by:

- a compressor;
- a condenser;
- an expansion valve;
- an evaporator.

The condenser and the evaporator consist of heat exchangers, i.e. tubes in contact with a service fluid (which may be water or air), and in which the refrigerant flows. This transfers heat to the condenser and absorbs heat from the evaporator. The components of the circuit can be either grouped together in a single block, or divided into two parts (**SPLIT systems**) connected by pipes in which the refrigerant flows. When the machine is working, the refrigerant within the circuit undergoes the following transformations (Figure 23.9):

- **adiabatic compression (1)**: the refrigerant fluid in gaseous state and at a low pressure coming from the evaporator is brought to high pressure; during the compression phase it heats up, absorbing a certain amount of heat;
- **isothermic condensation (2)**: the refrigerant fluid, coming from the compressor, moves from the gaseous to the liquid phase, releasing heat;
- **isenthalpic expansion (3)**: passing through the expansion valve, the liquid refrigerant fluid is partly transformed into steam and cools down;
- **isotherm evaporation (4)**: the refrigerant absorbs heat from the outside and evaporates completely.

Figure 23.9



The whole of these transformations makes up the **cycle of the heat pump**: by providing energy, by means of the compressor, to the refrigerating fluid, this, in the evaporator, absorbs heat from the surrounding medium and, by means of the condenser, releases it to the medium to be heated.

The advantage of using the heat pump lies in the fact that this system allows to provide more energy (in the form of heat, a form of energy of little value) than the electric power (a valuable form of energy) necessary to operate it. The environment from which heat is extracted is the cold source. The main cold sources are air, water, and soil.

The carrier fluid to be heated is called **heat sink**; usually, it is water or air.

In the condenser, the refrigerant transfers to the heat sink both the heat drawn from the source and the energy supplied by the compressor. The heat can then be transferred to the environment by means of ordinary coils inserted in the floor, radiators or fans-convectors (in the case of distribution with water circuit), or pipes for transferring heat to the different locations (in the case of the distribution of heat by air).

Depending on the type of cold source and heat sink used, heat pumps can be classified as: air-water, soil-water, water-water, air-air, water-air.

The performance of a heat pump varies considerably as a function of the temperatures of the cold source and heat sink. Specifically, the closer these temperatures are, the better the performance, both in terms of power supplied and in terms of COP. For this reason, it is advisable to use systems for the distribution of the heat operating at a temperature as low as possible.

As anticipated in paragraph 23.3, the COP represents the same concept seen for cold-generating refrigerator machines, i.e. the ratio between the thermal power transferred to the condenser and the power absorbed by the compressor:

$$COP = \frac{Q_{cond}}{P_{comp}} \tag{23.5}$$

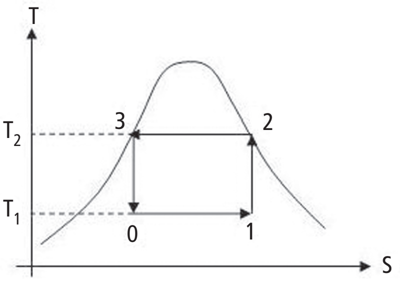
Considering the thermal powers in energy terms as the enthalpy difference between the end points of the transformations, it follows that:

$$Q_{\text{cond}} = h_2 - h_3 \qquad P_{\text{comp}} = h_2 - h_1$$

Replacing in (23.3), we obtain:

$$COP = \frac{h_2 - h_3}{h_2 - h_1} \tag{23.6}$$

The value of COP is usually between 3 and 4, depending on the type of heat type and the working principle, While the refrigeration cycle is irreversible, the operation of a heat pump is reversible; in fact, it is possible, by means of a valve, to swap the operation of the two exchangers, that will become, this way, evaporator and condenser. In summer cooling mode, the condenser is placed outdoors and the evaporator indoors, so that it behaves as a cooling system; in winter heating mode, their positions are swapped, so that the system behaves as a heat pump according to the diagrams in Figures 23.10 and 23.11.



Summer mode. The refrigerant, compressed by the compressor, is directed by the 4-way valve to the outdoor unit (which acts as a condenser), where it releases heat outdoors; then, it goes and expand in the thermostatically controlled throttling valve; the cold fluid exiting from the throttling valve goes to the indoor unit (which acts as an evaporator) and subtracts heat from the air of the room to be cooled down; then the fluid goes back to the 4-way valve that directs it toward the compressor.

CP	compressor
CN	condenser
VT	thermostatic expansion valve
VIC	4-way cycle inversion valve
EV	evaporator
VU	unidirectional (check) valve
FD	dehydration filter, to eliminate possible residual traces of humidity

Figure 23.10
Winter heating.

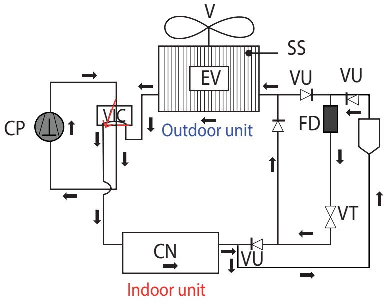
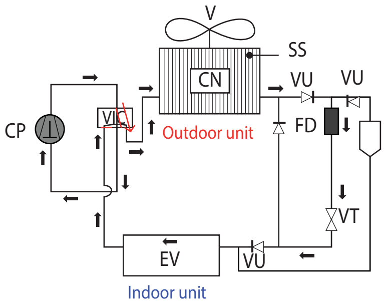
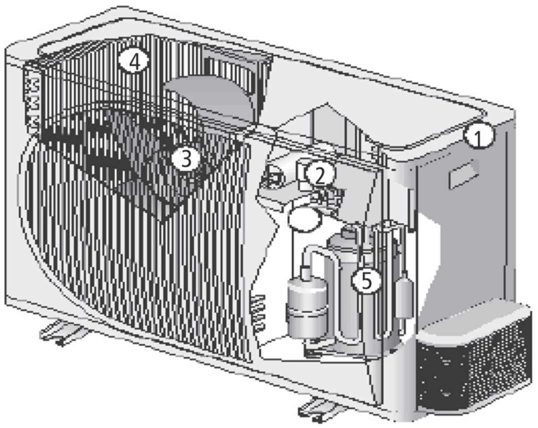


Figure 23.11
Summer cooling.



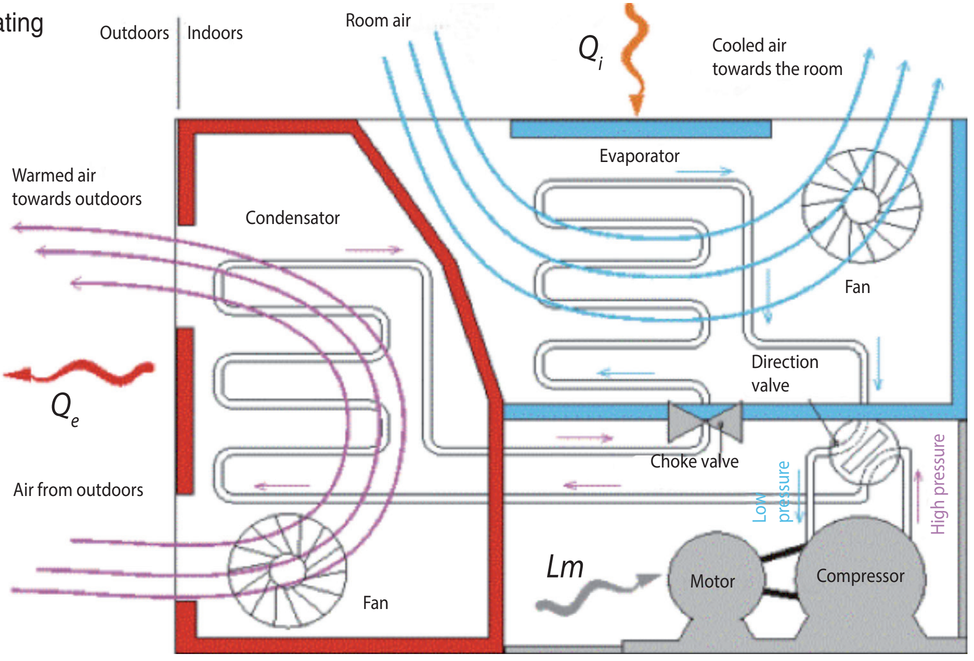
Outdoor unit

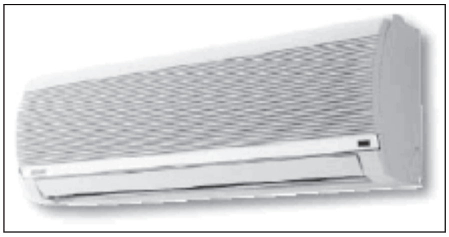


Cross section of an outdoor unit

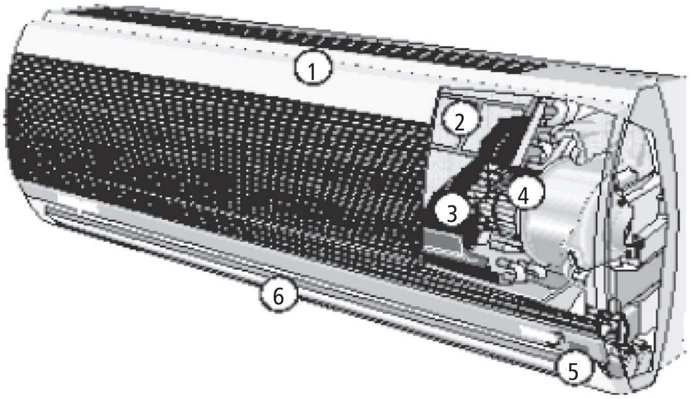
1 External cabinet
2 Control board
3 Fan group (motor + fan)
4 Heat exchanger
5 Compressor

Summer cycle
Example of the cooling of a generic house by heating outdoor air





Indoor unit

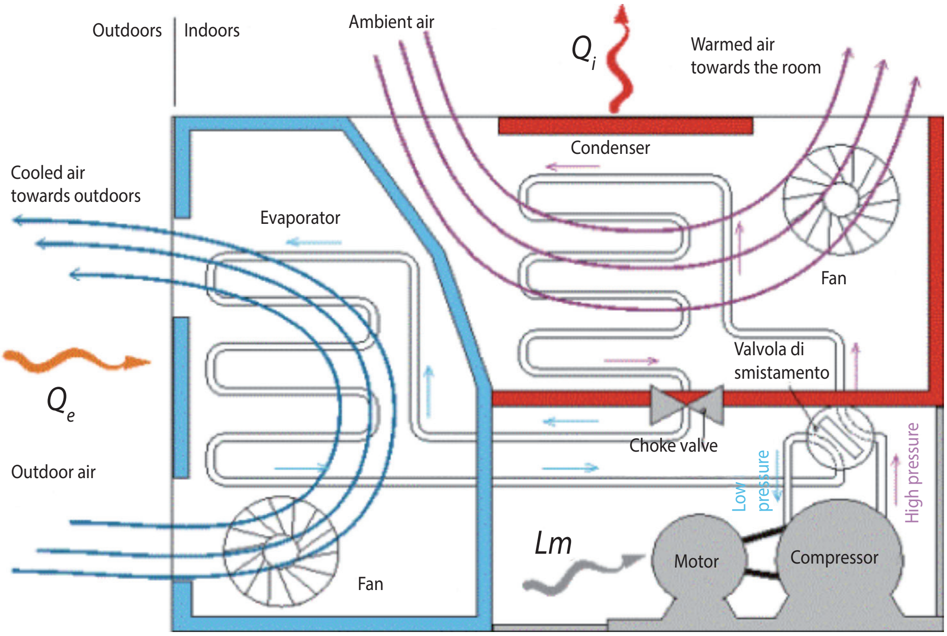


Cross section of an indoor unit
1 External cabinet
2 Air filter
3 Heat exchanger
4 Fan group (motor + fan)
5 Remote control receiver
6 Air flow deflector

Winter mode. The refrigerant, compressed by the compressor, is directed by the 4-way valve to the indoor unit (which acts as a condenser), where it warms up the air of the room to be heated; then it goes and expands in the thermostatically controlled throttling valve; the cold fluid exiting from the throttling valve goes to the outdoor unit (which acts as an evaporator) and subtracts heat from the outdoor air; then, the fluid goes back to the 4-way valve that directs it toward the compressor.

Following the new technologies on renewable sources of energy, one of the major applications of the heat pump is in the geothermal energy field. The only difference between a geothermal heat pump and a refrigerating unit consists in the desired effect, cooling for the refrigeration unit and heating for the heat pump.

Many heat pumps are, as already said, reversible and their operation can be reversed, since they can operate alternatively as a heating or cooling unit.



Winter cycle
Example of the heating of a generic house by cooling outdoor air

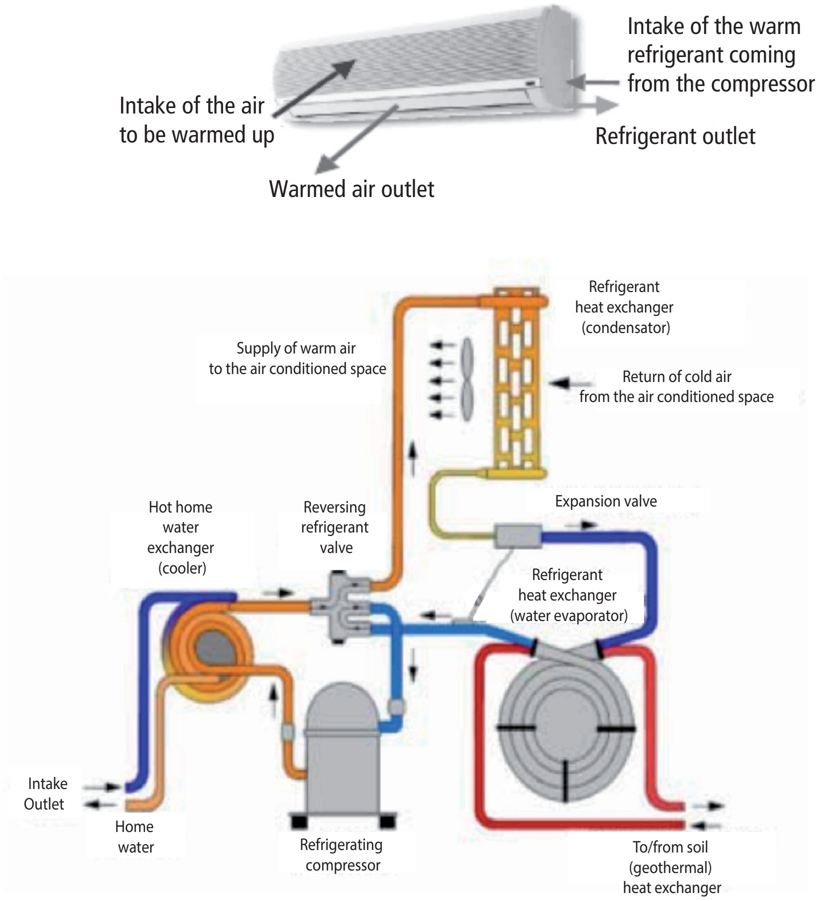


Figure 23.12

Heat pumps require electrical power to operate, but in suitable climatic conditions and with a good design, the energy balance is positive (Figure 23.12).

In Italy, heat pumps are still rather uncommon, but their use is spreading.

The energy balance of a heat pump is very different from that of a conventional combustion one. As it can be seen from the comparison of Figures 23.13 and 23.14, in the first case it is clear that a certain amount of the valuable energy provided by fossil fuel is lost and cannot be used by the user; in the second case, only a quarter of the valuable energy is used for the operation, the rest is absorbed from the low temperature source, as free heat. Currently, there are approximately 6000 installed units, and their number is growing at a rate of at least 500 units/year.

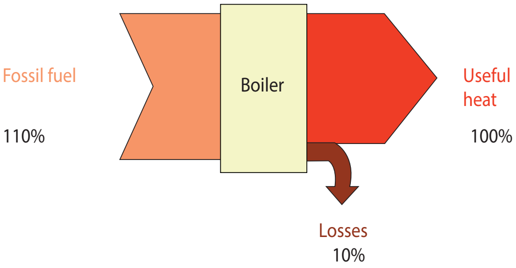


Figure 23.13

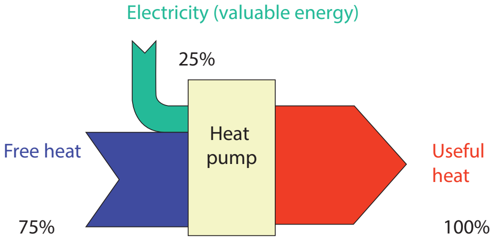


Figure 23.14

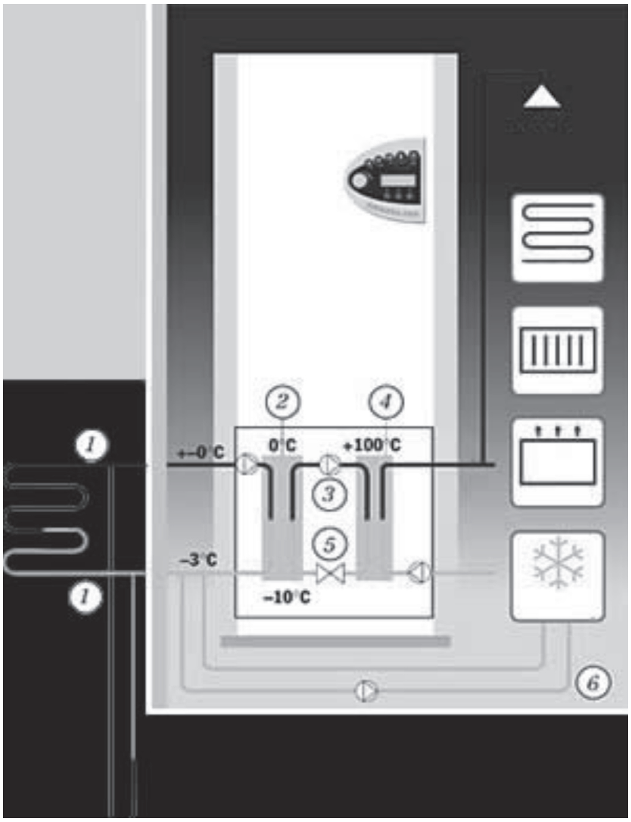


Figure 23.15

Another geothermal model based on IVT Inverter is shown in Figure 23.15.

As we can see, the plant can work both in summer and winter conditions, as explained below:

1. By circulating water and a non-toxic additive within geothermal exchangers of different shapes, the solar energy stored in the soil is extracted.
2. The liquid, through a heat exchanger, heats the refrigerant, that evaporates in a circuit inside the heat pump.
3. The refrigerant is compressed by a refrigerating compressor, which causes a considerable rise in its temperature.
4. The heat is transferred by means of a second heat exchanger (called condenser) to water for heating or for sanitary hot water.
5. The pressure of the refrigerant is lowered with an expansion valve; then, it moves to the evaporator to acquire new energy. In the case of a reversible heat pumps, the cycle is exactly the opposite, i.e. heat is removed from the surrounding environment.
6. There can be any kind of indoor heating systems: underfloor, in-wall, ceiling-mounted radiant panels, radiators, skirting board heating, fan convectors or air units; summer cooling can take place in a natural way, by connecting the geothermal heat exchangers (1) directly to the indoor system (passive cooling) or by using the reversible heat pumps (active cooling).

Heat pumps are the type of direct use of geothermal heat with the most intensive energy use and the greatest power installed.

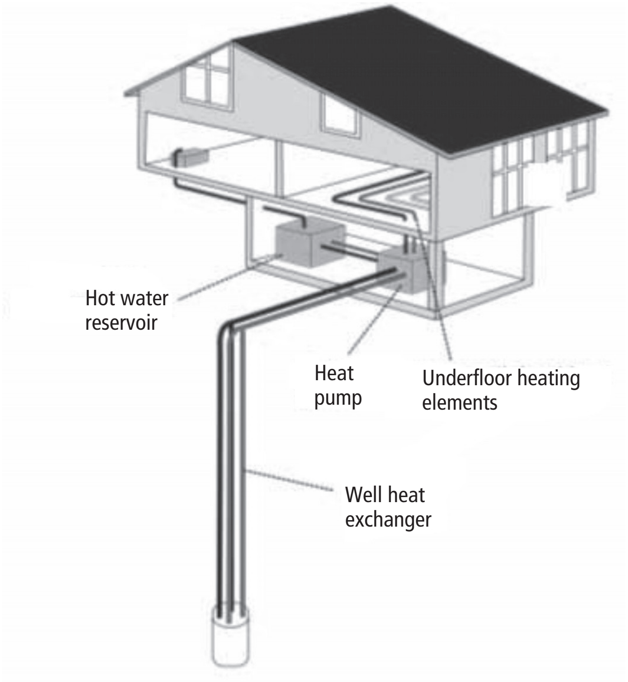


Figure 23.16

Currently, heat pumps are installed in 32 countries (mostly in North America and Europe) with about 1,3 million (equivalent) 12-kWt units. The different types of heat pumps available allow to extract and use at a low cost the heat contained in bodies at low temperature, such as soil, shallow aquifers, superficial water masses etc. (Figure 23.16).

23.6 Dimensioning of a refrigerating cell

As for the dimensioning of a refrigerating cell (Figure 23.17), which in fact corresponds to dimensioning of the evaporator, several parameters should be taken into account. In addition to the load due to the heat transmission, which influences the refrigerated space, through the walls, the floor and the ceiling, in order to choose the dimensions correctly it is important to calculate the loads of the heat generated by the handling of the product, by the internal sources, by the opening/closing of the doors and, finally, the load caused by the refrigerating equipment itself.

Before we begin, however, it is important to remember the definition of **thermal load**:

- variation of thermal energy occurring, in the unit of time, during the operation of a refrigeration cell, both positive and negative.

23.7 The refrigerator and its defrosting

Speaking in general terms, we can say that the refrigerators are divided into two broad classes: static and ventilated; the latter are the so-called **no-frost** appliances. **Static refrigerators** are so called because the transfer of cold in the compartments where the evaporators or cells are placed takes place by natural radiation, i.e. without the aid of fans designed to move the air. Depending on how the cabinet of the appliance is designed, we have:

Figure 23.17

- *single door refrigerators*, which have only one refrigerator compartment and often a two-star meat compartment in it;
- *top-mount refrigerators*, which have a three- or four-star freezer compartment at the top and a refrigerator compartment at the bottom;
- *bottom-mount refrigerators*, which have the refrigerator compartment at the top and the three or four-star freezer compartment at the bottom.

Bottom-mount fridges can have one or two compressors. In the latter case, there are basically two completely separate and independent refrigerating circuits, contained in a single cabinet.

The stars identify the temperature the meat compartment or the freezer can reach.

Therefore, in the case of a two-star compartment, the temperature is lower than –12 °C; in the case of a three-star compartment the temperature is –18 °C and, in the case of a four-star compartment, the temperature is lower than –24 °C. These temperatures can either be the lowest temperatures achievable by the device or they can be surpassed. In fact, the freezer compartment of a two-compressor bottom-mount appliance can reach without difficulty, depending on the settings of its thermostat, and/or other controls, temperatures lower than –24°C.

The cabinet of the appliance is the structure that supports the set of all the components and circuits necessary for the operation and inside of it, as said before, there are all the compartments for storing the food to be preserved or to keep frozen, within which their cold-producing evaporators can be found. The compartments are closed by doors equipped with magnetic gaskets whose purpose is sealing them as closely as possible, in order to keep the cold from escaping as much as possible and to prevent the warm ambient air from coming in. Between the outer and inner walls of the cabinet, and inside the doors, there is a foam of insulating material, whose purpose is, too, to maintain as much as possible the existing cold inside the appliance.

In the most popular models of refrigerators, the compressor is placed at the bottom of the rear part of the cabinet, while the condenser is placed along the wall (Figure 23.18).

Figure 23.18
Back of the refrigerator, with condenser and compressor

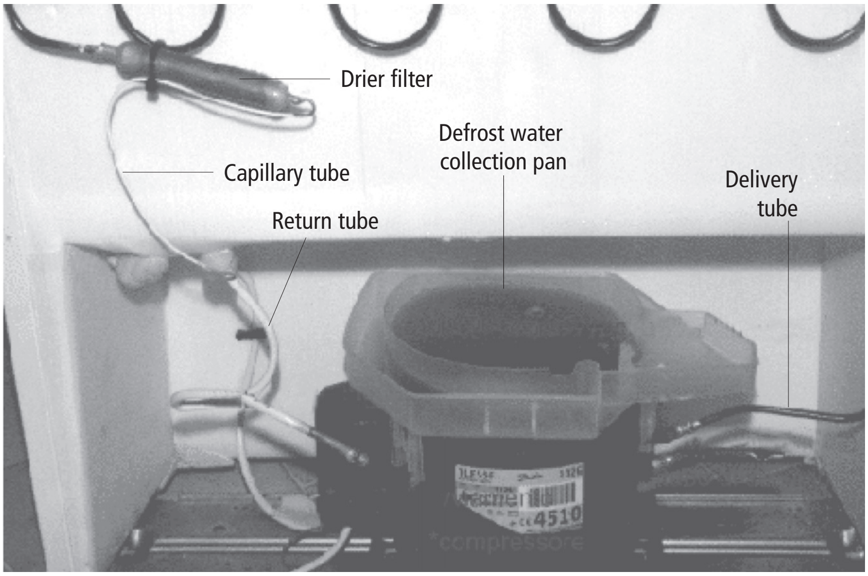


Figure 23.19 Detail of the compressor area.

The compressor is connected to the cooling circuit via two pipes: the delivery tube the compressor itself uses when “pumping” the refrigerant gas along the circuit, and the return tube, through which the gas returns to the compressor. There is a further piece of closed tube, the so-called *service line*, that is used to enter the gas when the device is being manufactured and that is also used for any subsequent charging operations (Figure 23.19).

When the appliance is turned on, by means of the thermostat, which also allows to set the desired temperature in the compartment it controls, electricity starts flowing to the starter unit connected to the compressor, and the latter starts running, compressing and pushing the refrigerant gas, through the delivery tube, in the condenser. At this stage, the gas is very hot and the condenser, a real dissipating surface, cools it by heating the external air, in order to make it liquid. Obviously, it follows that this heat exchange is very important for the proper functioning and optimum performance of the appliance. If the condenser is clogged with considerable deposits of dust, or it “works” in a confined space with only little air flow, the whole appliance may be negatively affected. Keeping on moving, the gas enters the anti-condensation pipe, directly welded to the condenser, which is still hot and, flowing within this tube, goes around the perimeter of the door of the freezer compartment.

(The anti-condensation pipe is usually immersed in the foam of the cabinet. This particular position depends on the fact that, this way, the jamb of the magnetic gasket of the freezer door is warmed up, preventing the creation of condensation.)

Now, the gas, cooled and liquefied, exits from the anti-condensation pipe and enters the drier filter, made up of hundreds of small balls that absorb any moisture contained in the refrigerant gas.

(This arrangement is very important, because the humidity, freezing inside the circuit, could cause clogs, hindering the optimal or total circulation of gas).

At the outlet of the drier filter, the gas enters the capillary tube, usually made of copper and, due to the forced pressure change, gets cold and at a low pressure, by means of the adiabatic transformation. Reaching the internal evaporator, in the refrigerator compartment, the gas expands and cools further down, absorbing the heat existing in this compartment, which is cooled down.

Continuing the cycle, the gas enters the capillary tube of the evaporator in the freez-

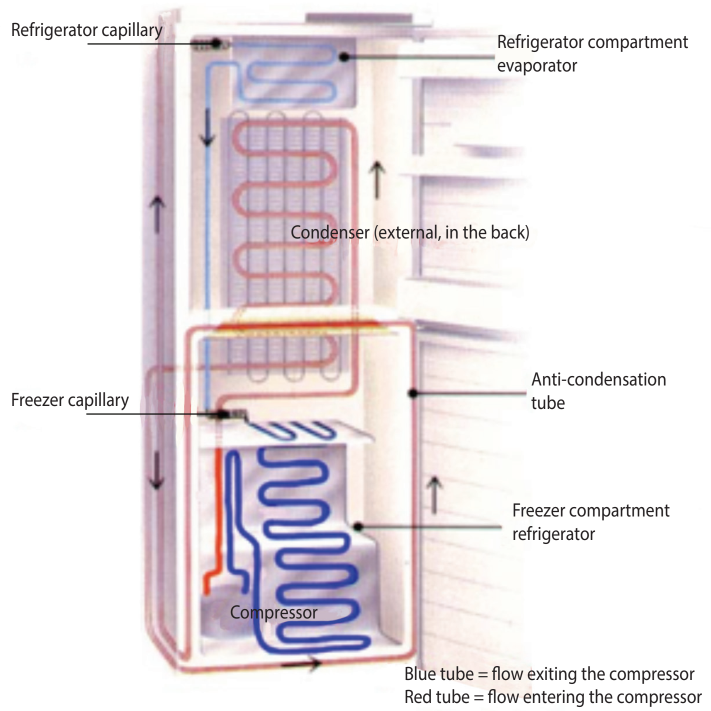


Figure 23.20 Diagram of the path of the refrigerator fluid in a common fridge.

er compartment, if present, where a second transformation similar to the previous one occurs. From here, via the return pipe, it returns into the compressor, since now the refrigerant gas has resumed its original gaseous state, and is easily sucked in by the compressor itself, which then pumps it back into the circuit through the delivery tube, beginning another cycle (Figure 23.20).

Defrosting

Cycles follow one another until the thermostat “feels” the temperature to which it has been set, through its bulb in contact with the refrigerator evaporator. This way, it opens the contacts controlling the compressor, stopping it. Now begins the defrosting stage of the refrigeration compartment evaporator. The frost that develops in this evaporator melts down, to avoid relevant ice formations, that must not be allowed to form in this compartment. Defrosting can be eased and made faster by an appropriate defrosting resistance.

This resistance, possibly fixed by means of plastic clips to the back of the evaporator, is moderately heated when it receives current from the thermostat, when this stops the compressor. The dissolving frost, turned to water, flows in the specific collection channel and from here, via a small tube, in a collection pan fastened to the “head” of the compressor. Thank to the heat of the latter, the same water evaporates, keeping it from accumulating.

The thermostat then “feels” the temperature rise at the end of the defrosting phase, opens the contacts that control the resistance and at the same time closes those that control the compressor, which starts a new cooling cycle.

Considerations and variants

The cycle described above refers to a bottom-mount refrigerator with a single compressor, in which the refrigerant gas passes first into the refrigeration compartment evaporator, and then in the freezer compartment one. In many cases, the opposite occurs. In appliances with a single compressor, there is only one thermostat that controls the refrigerator compartment. When the set temperature of the refrigerator compartment is reached, there is an exact and proportional temperature in the freezer. The defrosting time of the refrigerator evaporator does not have any negative consequences for the freezer compartment; however, sometimes, in order to ensure greater protection, the defrost phase is speeded up, as it has been said, by a suitable resistance.

In the case of bottom-mount appliances with two compressors, there are two separate thermostats that control two separate refrigerating circuits. There is no defrosting resistance in the refrigerator compartment. In addition that, it should be pointed out that, again referring to the construction of the refrigerant circuit, in most cases the capillary tube and the outlet and/or return tube of the evaporator are sheathed in a common tube, in order to ease the return of the refrigerant gas to the gaseous state, before it goes back into the compressor.

Considerations on the refrigerant gases used in circuits

When speaking of refrigerant gases, reference is made, at the present time and relatively to household appliances, to the possibility of using freon r12, the R134a gas, or the R600a gas. Freon R12 has been abandoned (it is no longer produced but it is still used when providing technical assistance for available appliances that still contain it) for a few years because it is pollutant and one of the causes of the “hole in the ozone layer”. Afterward, we moved to using first the R134a, still in use, and lately also the R600a, in many respects better than R134a.

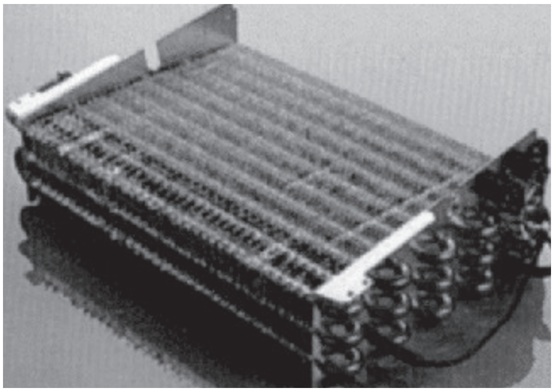
The no-frost refrigerator

Let us stop and consider the constructive difference between a static and a no-frost refrigerator.

No Frost means “without frost” and the main advantage that this type of household appliance offers with respect to the more traditional, static appliance, is that no frost is developed inside of the compartments, and therefore it does not require any manual defrosting operations even in the freezer compartment. The cold air is produced by a special evaporator (Figure 23.21) positioned in a suitable closed space between the refrigerator and freezer compartments or within the freezer itself.

The principle for which the evaporator produces cold is the same of the evaporators of static devices. After the thermal exchange occurred in the condenser, the refrigerant gas enters the drier filter and from here moves to the capillary tube, then enters into the evaporator with the right pressure and speed, and expands, therefore cooling down the airflow that suitable electric fans, typical of No Frost refrigerators, create and direct right inside the compartment containing the evaporator. The air, passing between the fins of the evaporator, transfers its heat and its humidity, exiting at several degrees below zero, then going to freeze and keep the food in the freezer compartment and to keep those in the refrigerator compartment. The air reaches the refrigerator compartment through suitable channels created under the coating of the inner back wall of the appliance and, even thought it comes from the evaporator at several de-

Figure 23.21



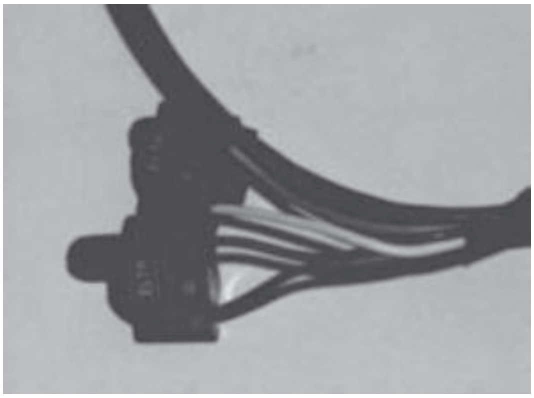


Figure 23.22

grees below zero, does not freeze the food because a dedicated thermostat stops the fan that delivers the air in this compartment, depending on the desired degree of cold.

It is clear, however, that the air that passes through the evaporator, more or less loaded with humidity depending on how many times the doors are opened and depending on the type of food that isentered, especially in the freezer, leaves in the evaporator itself a considerable amount of frost. This frost, if allowed to accumulate, causes the complete clogging of all the air inlet and outlet slits of the air, as well as the complete block of the electric fan placed directly in this box, completely stopping the cold production. Therefore, periodically, approximately every twelve or eight hours, a suitable timer causes the compressor and all the fans (normally two) to turn off, inserting a resistor placed in the evaporator itself (usually a 300 W one), which melts the frost.

Another resistance, with a lower power, is usually glued in the dish that collects and conveys the defrost water toward the outlet that is connected to the tube attached to the pad on the compressor head, where the water then evaporates. The main resistance remains engaged until the evaporator has reached a temperature that ensures the frost has completely melted. At this temperature, two special **thermostats** also called **bimetals** (Figure 23.22) kick off, directly bolted or fixed to a part of the evaporator, which disengage the same resistance so as not to cause too high a rise in the temperature in the freezer.

The pause set by the timer is usually around half an hour, a period of time during which the resistance glued to the plate remains normally in function, unlike, as said before, the main one controlled by the bimetals. If, however, in the default half an hour the bimetals themselves do not kick off, the defrosting pause remains in any case the same, and it is the timer that disengages the main resistance. After a few minutes, the same timer connects the compressor and the fans. Unfortunately, using a low-level defrost control type such as the one of a simple electromechanic timer, it is likely that after half an hour there is still some non-melted frost, which adds to other frost remained from following defrosting cycles. This causes, after a certain period of time and especially in the summer, a considerable accumulation of thick and hard ice in the container of the evaporator, which then blocks the entire operation of the appliance. Precisely for this reason suitable electronic control and management cards have been built and added to the not-frost appliances, which can employ more suitable defrost times and frequencies (see the paragraph "Fuzzylogic technology"). Once the compressor and the fans are back online, the compressor is controlled, until the following defrost cycle, by the main thermostat, which can also be of the four contacts type, therefore incorporating the control functions of the alarm light, and the blast-freezing setting control functions.

The refrigerator compartment is independently controlled by the dedicated thermostat that controls the corresponding fan, however it is normally subordinate to the main thermostat.

It is also possible to find, on the market, "hybrid" appliances, i.e. with the traditional, non-ventilated refrigerator compartment, equipped with its own evaporator, open or foam-enclosed, and a no-frost freezer compartment. Usually, in this case, if the appliance has one compressor, the main thermostat is the one that controls the evaporator of the refrigerator, but it is in any case still subject to the timer that controls the defrosting of the no-frost evaporator.

Fuzzylogic technology

***Fuzzylogic* technology**, applied to a domestic appliance, allows it to adapt automatically to all of the variables that come into play when, in the case of a washing machine, the laundry wash cycle starts, or in the case of a dishwasher that of the dishes, or even to manage, completely electronically and depending on the need, appliances such as refrigerators etc. This is obtained by means of high level electronic cards, equipped with management software of the household appliance, prestored in the microprocessors of the cards themselves. For example, there are washing machines equipped with this type of control that, once they have been started with the laundry to be washed, perform a whole series of "weighings", in order to provide the chip with the necessary information. In this way even if there are, for example, only a few base programs that can be set there is, in truth, an infinite combination of washing processes decided by the board. This kind of management is proving to be very useful, for example, also in case of no-frost refrigerators, constantly afflicted by problems linked to defrosting cycles that are often not enough to keep the internal evaporator free from ice, with the consequence that, especially during the summer period, in these refrigerators there is so much ice that the appliance cannot work properly. These high level electronic cards consider all variables, such as the number of times that the doors are opened or any residual amount of ice still present at the end of the defrost cycle etc., anticipating or delaying the successive defrosts. They can even take into account the temperature set for the freezer, automatically compensating those for the refrigerator, and they can control and manage a whole series of other parameters that are necessary to keep the compressor in good order, such as ambient temperature etc... It is clear that, if you have appliances equipped with such control systems, it is very important, in the case of failures, to contact always and only the technician authorized by the manufacturer, operating in your area of residence.

23.8 The absorption cycle

Absorption machines are used when there are large amounts of heat at low temperature. In fact, they exploit the heat transferred from a source at a temperature higher than room temperature that represents the hot source, in order to subtract heat from a cold source at a lower temperature than the ambient one. The block diagram of such a system is shown in Figure 23.23 and a complete example in Fig. 23.24.

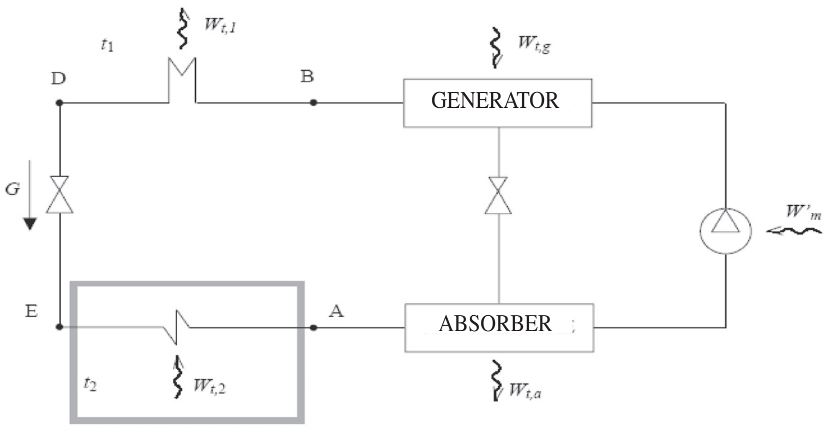
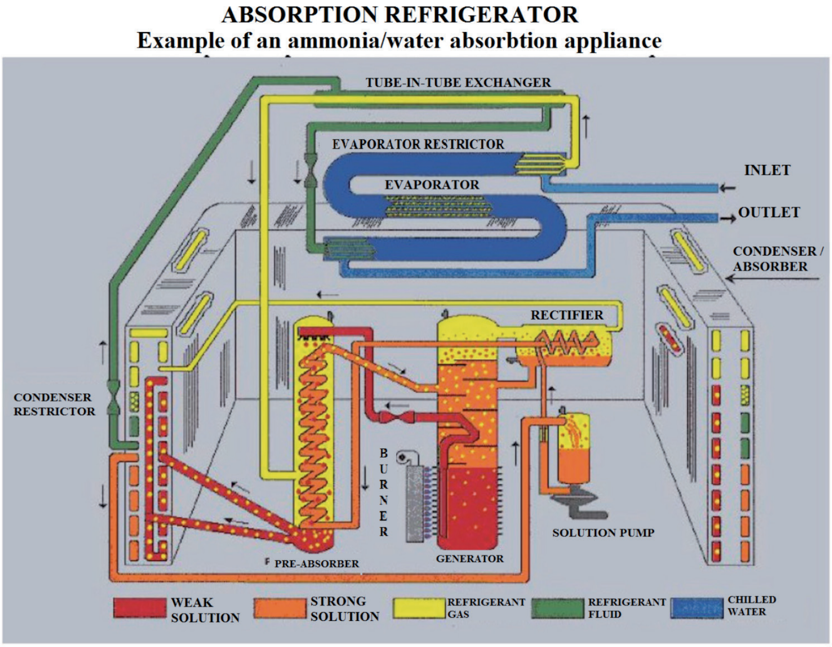


Figure 23.23

Figure 23.24



Initially, at point A, the refrigerating fluid (ammonia), in the dry saturated vapor state, enters the absorber, where it comes into contact with water at room temperature; here the ammonia (NH_3) bubbles and dissolves in water (H_2O), generating ammonium hydrate (NH_4OH), the solution is brought to pressure by the condenser by means of a pump, with only a limited amount of mechanical work being spent. Later, in the generator heat is provided to the solution, that becomes poorer of the solute (ammonia) delivered to the condenser; after the blow-by, the solvent goes back to the absorber, where it gains the ability to re-absorb the ammonia coming from the evaporator (in the frame in Figure 23.23). The dilution process of ammonia in water is exothermic, therefore it is necessary to subtract heat in the absorber, usually by using the same refrigerant used by the condenser.

Figure 23.25

A recent example application was built in a hotel in the Trentino province, in order to heat a swimming pool and also to cool and/or heat premises depending on the seasonal cycle. The heating systems, in addition to ensuring air conditioning in the premises of the hotel, also have the purpose of heating the swimming pool water and the sanitary water.

This way, GAHP-W (a Robur plant) (Figures 23.25 and 23.26) can provide power for both heating and cooling.

The unit can be switched on and off depending on the thermal need of the consumers; consequently, the machine will provide cooling power until the users require heating power. When the thermal load of the users is satisfied, the machine switches off.

This particular choice of control mode is motivated by the fact that the heating of the utilities of the hotel is characteristically continuous during the day.

When the unit is not in operation because of lack of thermal request by the system, in order to obtain a partial cooling of the premises t is possible to make direct use of aquifer water, as it used to happen with the system that was in place before the renovation.

The circulation of water in the two hydraulic circuits (hot side and cold side) is made possible and independent by two circulation pumps directed towards the unit. In summer mode, the thermal power is therefore used:

- in the boiler, with a coil heat exchanger, to heat sanitary water;
- in the stainless steel exchanger, to maintain the water of the swimming pool at a temperature of 26 °C.

The cooling power is used to create cooled water for the fancoil cooling system of the hotel.

The cold water exiting the fancoil system, before returning to the GAHP-W unit to be refrigerated again and brought to the design temperature, is directed in a plate heat exchanger in contact with the colder aquifer water, therefore undergoing a first pre-cooling thermal jump.

This simple solution has allowed to integrate the high efficiencies of the GAHP-W with the free energy of aquifer water.

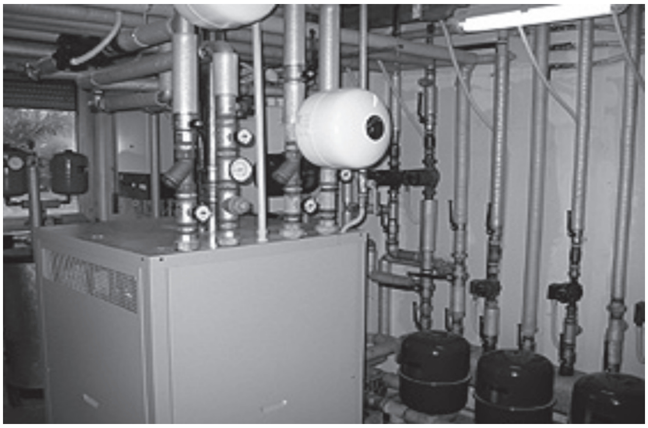


Figure 23.26