STRUCTURAL, FUNCTIONAL AND ENERGETIC MARKERS OF REFRIGERATING INSTALLATIONS

Vătavu Sorin, *Associate Professor, Ph.D. Eng, University of Petroşani*
Vătavu Niculina, *3rd degree Scientific Researcher, Ph.D. Eng. INCD-INSEMEX Petroşani*

Abstract: *Cold engineering assesses and manages processes and establishes calculation programmes and constructive solutions for the development of machineries and installations which operate within a wide range of temperatures, the field of cold engineering and air conditioning covering a large domain comprising the following sectors: industry, environment, transports, commerce, tourism, health and household. Refrigerating installations comprise, from an operational, energetic and constructive point of view, two types of thermal installations which operate on the same type of thermodynamic cycles: the actual refrigerating installations and the heat pumps; these two types of installations are not different from an operational point of view, the differences consist in the ranges of temperature they operate.*

The thermal and physical processes which compose the operating cycles of the refrigerating installations are, mainly, less known than the ones met in different types of installations, such as heating installation. The starting point of the analysis of refrigerating installations should be the appointment of the operating principle, the study of refrigerants and the establishment of the principles for their thermal calculation.

Key words: *cold engineering, refrigerating installations*

1. INTRODUCTION

Refrigerating installations deal, from an operational, energetic and constructive point of view, with two types of thermal installations which operate according to the same type of thermodynamic cycles: i.e. refrigerating installations and heat pumps. The differences between these installations are not operational but the range of temperatures within which they operate, therefore the problems occurring with the refrigerating installations may be extrapolated to heat pumps as well.

Refrigerating installations are met and used in different activity domains with specific destinations for each and every one:

- In apartments, offices, hotels, restaurants or public spaces, they are used for: food storage and preservation and air conditioning;
- the food industry uses them for the realisation of technological processes or for food storage and preservation;
- the chemical industry uses them to ensure the conditions for a series of chemical reactions to occur;
- the mining industry, car industry and medical industry and pharmaceutics uses them to carry out a series of technological and manufacturing processes as well as for storage and preservation.

The essential role of low temperatures used in the food industry is to preserve food by creating specific conditions, the artificial cold contributing to slowing down or stopping the biological, physical-chemical and biochemical changes of the preserved produce.

2. GENERALITIES CONCERNING THE USE OF COLD ENGINEERING

Cold engineering analyses and manages phenomena and processes occurring between approximately 373.15 K (+100 °C) and 0 K (–273.15 °C), establishes calculation programmes and constructive solutions for the development of machineries and installations which operate within a wide range of temperatures [1], [2]:

- heat pumps, for (+40 ... +100)°C;
- air conditioning installations, for (0 ... +5) °C;
- industrial cold air installations, for (–200 ... 0) °C
- and cryogenic and deed cold installations, for (–273.15 ... –200) °C respectively (0 ... +73.15) K.

The most important production corresponds to industrial air, and the most important cold consumers are found in:

- the chemical industry which uses the largest amounts of cold, with constant parameters, required for the following specific processes:
  - evacuation of mixture and reaction heat;
  - the separation of salts from liquid solutions;
  - liquefaction of a series of gases, etc.
- the food industry requires low temperatures for:
  - their commercial network;
  - food storages,
  - different technological processes;
- the mining industry and hydro-technical and infrastructure works use cold engineering to freeze the soil in order to carry out the construction of galleries or underground works;

- the car industry, for thermal treatment, hooping assemblies, special chipping processing, etc.;
- constructions for soil freezing, cooling down the components before pouring the concrete, etc.;
- research laboratories to study the behaviour of materials and machineries in low temperature conditions.

The development of cold engineering, with applications in the field of air conditioning, meets the requirements of comfort conditions, heating during winter using heat pumps or air cooling during summer with temperature and humidity control in living spaces, cultural and commercial spaces, means of transport, or other destinations, as well as ensuring the right conditions to carry out the technological processes. The technological processes which require a controlled environment are met in different sectors such as:

- the food industry, in the production of beverages and alcohol, meat, fruit and vegetable freezing, safely preserving cheese and dairy products and mainly all food produce;
- electronics, where the operation conditions suppose most of the times strictly controlled thermal regimes;
- the textile industry, where the humidity conditions are strictly controlled, etc.

3. FUNDAMENTAL MARKERS OF REFRIGERATING INSTALLATIONS

The thermal and physical processes which compose the operating cycles of the refrigerating installations are less known than the ones met in other types of installations such as heating installations.

According to the second principle of thermodynamics, any body may be naturally cooled down to reach temperature of its surrounding environment, cooling it down even more being possible only artificially using specific systems and installations.

Artificial cold producing installations, also called refrigerating installations (RI), are capable of decreasing and maintaining the temperature of a body or of a system of bodies bellow the temperature of the environment, at least two bodies taking part in the cooling process: the body which is cooled down and the one carrying out the operation, which is also called *refrigerant*.

Three main classification criteria may be identified for the RI used in industry, commerce, medicine and household appliances:

1. According to their **operation principle,** they may be:

- with mechanical vapours or gases compression;
- with absorption / thermodynamic compression;
- with egestion and
- thermo-electrical.

Mechanical compression RIs use the elasticity of vapours and gases, which bear an increase of temperature when compressed and a decrease of temperature during the relaxation process.

Absorption of thermo-chemical compression RIs operate through the successive realisation of thermo-chemical reactions, first of absorption of the refrigerant by an absorbent followed by the desorption of the agent from the absorbent. The absorption and desorption processes are similar to the aspiration and evacuation processes carried out by the mechanical compressor.

Egestion RIs use the kinetic energy of a vapour or gas jet and may be either with ejector or vortex motion.

Thermo-electric RIs are based on the Peltier effect and allow for the artificial cold to be obtained based on electric phenomena: when the electric current passes through a set of different bodies, the appearance of temperature differences in the area where the materials touch is observed.

2. According to **the refrigerating cycle,** they may operate:

- in a closed process and
- in an open process.

The operating agent of the *IF closed process* passes through the composing elements in an enclosed framework, its temperature operating between the two imposed limits by the two heat sources: cold and hot. They comprise the mechanical vapour compression installations, with absorption, with ejector and some with gases mechanical compression.

The operating agent of the *IF open process* is completely or partially extracted from the installation, being replaced with fresh operating agent.

3. According to the **operating period,** they may be:

- with continuous operation, in a stationary regime,
- and with discontinuous operation, in a non-stationary regime.

4. REFRIGERATING INSTALLATIONS' OPERATING AND CALCULATION PRINCIPLES

Refrigerating installations, [1], [2] şi [3], are a part of thermal installations: they take over the heat from a low temperature environment and transfer it to an increased temperature environment, phenomenon which may also be observed on the energetic diagram in Figure 1.

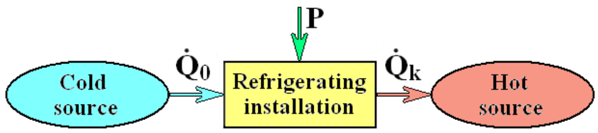


Fig. 1 Refrigerating installation: energetic diagram.

The lower temperature environment, from which the heat is taken over, is called the *cold source*, while the increased temperature environment, to which heat is transferred, is called *the hot source*. As heat sources have an infinite thermal capacity, their temperatures remain constant even the sources exchange heat.

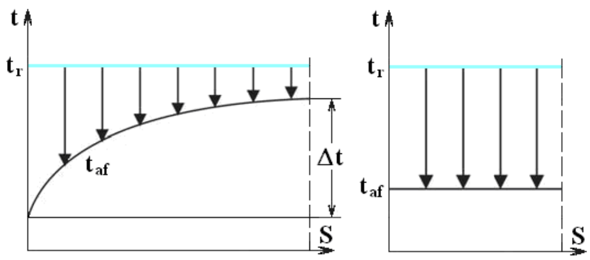
The heat flow absorbed from the cold source is marked with $\dot{Q}_0$, while the heat flow transferred to the warm source is called - $\dot{Q}_k$; according to the second principle of thermodynamics, for heat transport, considering the presented conditions, an energetic consumption called P is required.

Considering the refrigerating installations, the temperature of the cold source is found below the temperature of the environment, and the process of lowering the temperature below this value is called artificial cooling.

The agent operating within these installations is called *refrigerant* (RA): in order to take over the heat from the cold source, the temperature of the refrigerant has to be lower. During temperature take over from the cold source, the RF may have two different behaviours:

- its temperature increases, heating up (Figure 2,a);
- its temperature remains constant (Figure 2,b).

The two possible temperature variation of the RA (t_{af}) along the heat exchange surfaces (S), are presented in Figure 2: the temperature of the cold source was marked with (t_r), while the arrows represent the direction of the thermal transfer (from the cold source to the refrigerant). It is obvious that maintaining a constant temperature of the RA during heat transfer is possible only if the state of aggregation is changed, namely *vaporization.*



a. b.

Fig. 2 Heat absorption by the RA from the cold source.

The calculus relations for the *absorbed heat* (Q_0) in the two cases are the following:

- *for the case without the change of the state of aggregation,*

$$Q_0 = m_{afi} \cdot c_p \cdot \Delta t, \quad [\mathrm{kJ}], \tag{1}$$

where m_{afi}, [kg], is the amount of operating agent which heats up, c_p, [kJ/(kgK)] is the specific heat, while Δt, [K], is the inlet and outlet temperature variation of the refrigerant, in thermal contact to the cold source;

- *for the case with the change of the state of aggregation*,

$$Q_0 = m_{afv} \cdot \lambda_v, \quad [\mathrm{kJ}], \tag{2}$$

where m_{afv}, [kg], is the amount of operating agent which vaporizes, and λ_v [kJ/kg] is the latent specific vaporising heat of the refrigerant, reaching the vaporising temperature t_0.

In order to have an efficient thermal transfer, Δt is limited to some degrees. The heat exchange at finite temperature differences is accompanied by internal nature irreversibilities and the higher the temperature differences are the less efficient the thermal transfer is. Therefore it is more preferable to have the scenario with the change of the state of aggregation, to which it corresponds a constant temperature of the RA and a constant temperature difference, which may be decreased using technological solutions. Considering the case without the change of the state of aggregation, in order to absorb more heat it is required heat up the refrigerant more accompanied as well by the increase of the medium temperature difference from the cold source, therefore an emphasised irreversible character.

If the continuous operation case of these types of installations is taken into consideration, the characteristic measure for the intensity of thermal transfer is no longer the heat but the *thermal flow* absorbed by the RA from the cold source, or the thermal charge or the thermal charge of the vaporiser, measure market $\dot{Q}_0$. This measure is also called *thermal power*, and in the case of RI – *refrigerating power*. In order to rewrite relations (2.1) and (2.2) using this measure, the RA quantities - m_{afi} and m_{afv} need to be replaced with *mass flows*, marked $\dot{m}$: if relations (1) and (2) are divided with time, it is then obtained:

$$\dot{Q}_0 = \dot{m}_{afi} \cdot c_p \cdot \Delta t, \quad [\mathrm{kW}] \quad \text{and} \tag{3}$$

$$\dot{Q}_0 = \dot{m}_{afv} \cdot \lambda_v, \quad [\mathrm{kW}]. \tag{4}$$

Therefore, the thermal transfer between the cold source and the refrigerant when the later vaporises is characterised by mass flows which are more reduced than in the absence of the change of the state of aggregation.

In order to transfer heat to the warm source, the temperature of the refrigerant RA needs to be higher than the one of the source. While heat is transferred towards the warm source, the behaviour of the RA may be the same as in the case of thermal interaction with the cold source, in the same two different ways:

- it may cool down reducing its temperature (Figure 3,a);
- its temperature remains constant (Figure 3,b).

The two possible temperature variations (t) of the operating agent, along the heat exchange surfaces (S), are presented in Figure 3: where t_c is the temperature of the hot source, and the arrows represent the thermal transfer (from the RA with temperature (t_{af}) towards the source).

It becomes obvious that keeping the temperature of the RA constant during heat transfer is possible only if the state of aggregation is changed, namely if *condensation* occurs.

For a continuous operation of these types of installations, using the thermal flow transferred by the refrigerant to the warm source, the thermal charge, or the thermal power of the condenser, measure marked with $\dot{Q}_k$ and the mass flows marked $\dot{m}_{afi}$, and respectively $\dot{m}_{afc}$, are:

$$\dot{Q}_k = \dot{m}_{afi} \cdot c_p \cdot \Delta t, \quad [\mathrm{kW}] \quad \text{and} \tag{5}$$

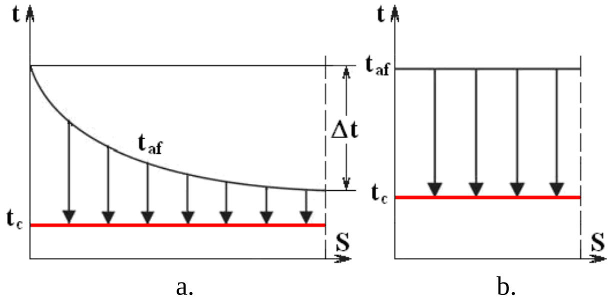


Fig. 3 Heat transfer from the RA to the cold source.

$$\dot{Q}_k = \dot{m}_{afc} \cdot \lambda_v, \quad [kW]. \tag{6}$$

Moreover, the thermal transfer between the refrigerant and the heat source in the conditions of changing the state of aggregation is characterised by more reduced mass flows than in its absence. This aspect has important implications on the entire installation: lower flows mean lower energy consumption for the transport of RA, reduced pipes' diameters, respectively smaller geometric elements considering the dimensions of the heat exchangers. For reasons previously presented, considering the majority of the refrigerating installations, it is preferable to have a thermal transfer between the operating agent and the heat sources through the change of the state of aggregation.

The two devices of the RI touching the heat sources are the most important components of these types of installations and are therefore called: *vaporiser* (marked V) and *condenser* (marked K): the useful effect of the refrigerating installation or the artificial cold is realised in the vaporiser, by taking over the heat of the cold source.

According to the second principle of thermodynamics, heat cannot transfer by itself from a low heat source (the cold source) to a higher heat one (heat source): the phenomenon is possible in an RI only with an energy consumption (either mechanical or of another nature) from the exterior. The outer energy consumed for the operation of the installation is either a mechanical or a thermal power, and it was marked P in Figure 1.

If an energetic balance is carried out for the refrigerating installations or for the heat pumps, respectively is the first principle of thermodynamics is applied, it may be observed that the sum of the inlet energy, namely the thermal charge of the vaporiser $\dot{Q}_0$ and power P, is equal to the output energy of the system and namely the thermal charge of the condenser $\dot{Q}_k$:

$$\dot{Q}_k = \dot{Q}_0 + P, \quad [kW]. \tag{7}$$

Temperature t_0 at which the refrigerant vaporises, also called *vaporising temperature,* has a corresponding unique saturation pressure, marked p_0 which is called *vaporising pressure*. Analogically, temperature t_k at which the refrigerant condenses called *condensing temperature* has a corresponding *condensing pressure* p_k.

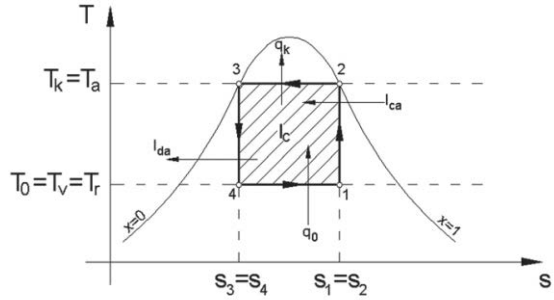


Fig. 4 Reversed reversible Carnot cycle in a moist vapours field.

As the temperature of the RA in any spot of the vaporiser is smaller than the temperature of the cold source, as presented in Figure 2,b, then it may be observed that $t_0 < t_r$. Analogically, as the temperature of the RA in any spot of the condenser is higher than the temperature of the heat warm source, as presented in Figure 3,b, it may be then observed that $t_k > t_c$. As the temperatures of the heat sources are in an obvious relation $t_c > t_r$, it clearly results that the condensing temperature is higher than the vaporising one ($t_k > t_0$), therefore it is also obvious that $p_k > p_0$: the values of the vaporising and condensing pressures shall be ensured by the vaporiser V and respectively the condenser K.

The heat transport from the cold source to the warm one is realised with the minimum possible energy consumption through a reversed reversible, which shall be realised in a field of moist vapours as it may be observed in Figure 4.

The operating process occurs between the vaporising temperature T_v, = T_0, theoretically equal to the temperature of the cold source T_r, the condensing temperature T_k, theoretically equal to the temperature of the warm source T_a (of the environment) and the two reversible adiabats (s = constant): i.e. the compression and respectively the relaxation, the direction of the cycle being anticlockwise. The operating agent takes over heat in the vaporiser of the installation through the isobaric-isothermal process 4 – 1, after which the obtained vapours are adiabatically reversibly compressed, through process 1 – 2; after is being delivered by the compressor, the operating agent reaches the condenser where it transfers heat to the isobaric-isothermal process 2 – 3, the resulted liquid relaxes then into the cycle breaker, the operating cycle 3 – 4 of this device also being reversibly adiabatic and it is repeated.

In the case of cyclic operation of refrigerating installations, the composing operating agents take over the heat when they vaporise at low temperatures and give up heat when they condensate at temperatures close to the one of the environment: these agents need to be therefore characterised by a series of particular properties which differentiates them from the thermodynamic agents from other types of installations.

The properties of refrigerants are imposed by the diagram and the type of installation, as well as by the levels of temperature of the two heat sources.

Not to use complicated chemical denominations of these substances, the refrigerants were generically called *freons,* and the used symbol is R (from the

English *refrigerant*), and were associated with a number depending on their chemical composition, being able to divide them into three large categories:

- CFC (chlorofluorocarbons) – classic freons, the molecule of which contain very instable chloride,
- HCFC (hydrochlorofluorocarbons) – transitional freons the molecule of which also contains hydrogen due to which the chloride is much more stable and does not decompose that easily under direct ultraviolet radiations,
- HFC (hydrofluorocarbons) – definitive substitution freons which do not contain chloride atoms at all and are very environmental friendly,

The last category being recommended for present RI.

5. STRUCTURAL AND OPERATIONAL PARTICULARITIES OF REFRIGERATING INSTALLATIONS WITH THE VAPORISATION OF THE REFRIGERANT

As it was mentioned before, the value of the condensation pressure is higher than the vaporising one ($p_k > p_0$), therefore the refrigerating installations RI consume energy to increase the pressure of the vapours delivered by the vaporiser (where the refrigerant RA passes as vapours taking over heat from the cold source) to the pressure from the condenser (where vapours condensate and give up heat to the warm source): this process may also take place in a *compressor unit,* with the help of a mechanical energy consumption.

If the vaporiser and the condenser are heat exchangers and contain a thermal transfer surface in order to ensure the interface between the RA and the heat sources, the compressor is constructively a complex machinery: a piston inside a cylinder, with a bolt, with sliding blades inside a rotor placed before the stator, or with different constructions, in these cases the compression being realised by reducing the volume of the used refrigerant. There are turbo-compressors, their operation being based on the laws of gas dynamics, being able to transform kinetic energy into pressure potential energy. The exterior necessary power for the process to be carried out, called *compression power*, is marked P_c.

After the compression takes place, the vapours from the RA give up heat through the condenser to the warm source and condensates at the p_k pressure value, namely at the end of the process the refrigerant leaves the heat exchanger as a liquid.

In order to return to the vaporiser, the moisture needs to reduce its pressure to p_0. From an energetic point of view, the relaxation is carried out efficiently in a device called *cycle breaker.* Its advantage is that it produces energy, respectively mechanical energy capable to compensate a part of the necessary consumption for the compressor to operate. Constructively, the cycle breaker is either a machinery with one piston in a cylinder, or a radial or axial circulation of the refrigerant. Independent of its construction, the operating agent transfers to the piston or the rotor some of its potential pressure energy and relaxes therefore to reach the vaporising pressure. The energy supplied during relaxation, called *relaxation energy* is marked P_d.

The liquid RA at a pressure p_0 enters the vaporiser where it absorbs heat from the cold source, vaporises and then enters in the compressor, the operation of the installation being therefore cyclical, and goes through successive-continuously through all four components. The processes taking part here, respectively vaporisation, compression, condensation and relaxation make together the *ideally reversed thermodynamic cycle* (Figure 4), according to which both the RI and the heat pumps operate.

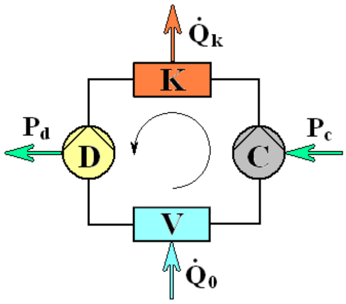


Fig. 5 Structural and energetic diagram of the RI with the vaporisation of the RA.

It results therefore that the RIs are composed of at least four elements: the vaporiser (V), the compressor (C), the condenser (K) and the cycle breaker (D), and the simplest constructive diagram for such installations may be similar to the one presented in Figure 5.

Most of the times, the cold source or the environment cooled down by the vaporiser is represented by air, water or other liquids around the heat exchanger, generically called *intermediate agents*: practically, the refrigerant vaporises absorbing heat from these substances.

For the condenser, the heat source or the heated environment is represented by environmental air, water or air and water simultaneously. These parts, through their heat exchange surface, take over all the latent heat from the condenser. Therefore water or air are cooling agents for the condenser.

Power (P) necessary from the exterior for the operation of the RI is represented by the difference between the compression energy (P_c) and the relaxation energy (P_d):

$$P = P_c - P_d, \quad [\text{kW}]; \tag{8}$$

the energetic balance equation (7) remains valid.

Considering the energetic analyses, in order to eliminate the dependency on the quantity of substance, respectively of the mass flow of the operating agent in the installation, the specific energetic exchanges may be taken into consideration, namely, in relation to a kilogram of substance. These are:

- The specific refrigerating power:

$$q_0 = \dot{Q}_0 / \dot{m}, \quad [\text{kJ/kg}]; \tag{9}$$

- The specific mechanical work of compression:

$$l_c = P_c / \dot{m}, \quad [\text{kJ/kg}]; \tag{10}$$

- The specific thermal charge of the condenser:

$$q_k = \dot{Q}_k / \dot{m}, \quad [\text{kJ/kg}]; \tag{11}$$

- The specific relaxation mechanical work:

$$l_d = P_d / \dot{m}, \quad [\text{kJ/kg}]. \tag{12}$$

The cycle breaker from the refrigerating installations could be a very complex machinery and therefore very expensive, having an unjustified use for the production of a useful effect: the relaxation of the RA occurs when it is mostly in liquid form (the liquid supplied by the condenser goes into the cycle breaker) and it is well known that with the relaxation of the liquid a mechanical work occurs which is more reduced than in the case of vapours' relaxation.

Practically, the cycle breaker of the RI is replaced by a much simpler device where the relaxation occurs through lamination: this is either a capillary tube, within the reduced refrigerant power systems, or a lamination valve, within the medium or large refrigerant power ones. The RIs containing these relaxation devices called lamination devices - LD (Figure 6), are less efficient than those presented in Figure 5 as they no longer produce a mechanical work, respectively relaxation power, but they are more technical-economical efficient, practically representing the only technical solutions presently used in building mechanical vapours compression RIs.

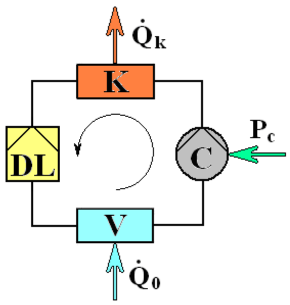


Fig. 6 Structural and energetic diagram of RA vaporisation RI, with lamination device.

Mechanical vapours compression refrigerating installations, generally called VRI, are used to obtain temperatures within the range –20 … –90 °C and they may be:

- A single step compression operated: for the temperature range –20 … –30 °C, with the tendency of reaching –60 °C by perfecting the cycle (advanced under-cooling before lamination, overheating the vapours absorbed by the compressor, using superior performances refrigerants);
- Two or three steps compression operated: they are used for the temperature range –30 … –60 °C and they operate with only one refrigerant;
- In cascade: they are used to obtain temperatures within the range of –70 … –90 °C, the cascade being run through by different refrigerants.

The main advantage of VRIs is that, when changing the state of aggregation through vaporisation and condensation, the values of the heat transfer coefficients are increased, and therefore the heat exchangers of the refrigerating circuit may be dimensioned in economical conditions. In the case of pure fluids, the two processes are isothermal, reducing losses due to the irreversibility of the heat exchange between the RA and the two heat sources, by maintaining the minimum temperature differences within acceptable limits. This type of refrigerating installations is widely used in cold engineering.

6. CONCLUSIONS

Refrigerating installations are capable of reducing and maintaining the temperature of a body or of a system of bodies below the environmental temperature, in the cooling process being involved at least two bodies: namely the body which is cooled down and the body which carries out the process also called refrigerant; the refrigerant takes over heat from a low temperature environment and transfers it to another one with an increased temperature.

Mechanical compression refrigerating installations use the elasticity of vapours and gases which are able to bear a temperature increase when compressed and a temperature decrease when relaxed: these installation consume energy to increase the pressure of the vapours supplied by the vaporiser (where the refrigerant passes as vapours taking over heat from the cold source) to the pressure value in the condenser (in which the vapours condensate and transfer heat to the warm source / the environment), the process being carried out inside a compressor unit. These installations are composed of at least 4 elements: the vaporiser, the compressor unit, the condenser and the cycle breaker, this last one may be replaced by a laminating device: the values of the heat transfer coefficients are increased when the state of aggregation is changed through vaporisation and condensation, therefore the heat exchangers from the refrigerating circuit (i.e. the vaporiser and the condenser) may be dimension economically.

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