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White paper

Natural Refrigerants

High efficiency solutions

New developments in HVAC/R systems, driven by an increasingly competitive market and more restrictive regulations, are moving in the direction of reducing total CO_2 emissions. On one hand, the use of natural refrigerants rather than synthetic ones such as HFCs drastically reduces direct CO_2 emissions. Nonetheless, this can only be accompanied by efficient systems that also help reduce indirect CO_2 emissions. When combining natural refrigerants and high efficiency, the use of the best technology becomes especially relevant, considering the unique characteristics of natural refrigerants, such as high pressures in R-744 (CO_2) cycles and the flammability of hydrocarbons.
This document is a compilation of the theory on natural refrigerants as well as energy saving technologies available to optimise their use and obtain systems with the lowest total CO_2 emissions.

Do not hesitate to contact us for further information about the contents of this paper:

Knowledge
Center

CAREL Industries
carel@carel.com
(+39) 0499 716611

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Definition of terms

EC fan: electronically-commutated (EC) fan with a brushless, permanent magnet DC motor and integrated electronics for controlling the fan rotor.

GWP (Global Warming Potential): characteristic factor estimating the greenhouse effect of a gas being released into the atmosphere compared to the effect of R-744. For example, the GWP of R-744 is 1 and the GWP of R-134a is 1430: this means that 1 kg of R-134a has the same greenhouse effect as 1430 kg of R-744.

HC (Hydrocarbons): substances composed of hydrogen and carbon. These are natural, non-toxic refrigerants that have no ozone depleting properties (ODP) and minimal GWP. E.g.: R-290 (propane).

HCFC (Hydrochlorofluorocarbons): substances containing hydrogen, fluorine, carbon and chlorine. These are considered the "second generation" of synthetic refrigerants, substituting CFCs (chlorofluorocarbons) such as R-12. HCFC refrigerants have ODP and are greenhouse gases (high GWP), e.g. R-22.

HFC (Hydrofluorocarbons): substances containing hydrogen, fluorine and carbon. These are considered the "third generation" of synthetic refrigerants, with no ODP, but are greenhouse gases (high GWP). E.g. R-134a, R-32, R-404A.

HFO (Hydrofluoroolefins): substances comprising hydrogen, fluorine and carbon. These are considered the "fourth generation" of synthetic refrigerants, with a thousand times lower GWP than HFCs. E.g. R-1234yf, R-1234ze(E).

ODP (Ozone Depletion Potential): potential for a single molecule of refrigerant to destroy the ozone layer, with R-11 being fixed as a reference at an ODP of 1.0.

Seasonal efficiency: efficiency ratio of an application at standard rated conditions, representing the variations in load and ambient temperature throughout the year.

Superheat: difference between the actual temperature of the refrigerant vapour and the saturation temperature of the refrigerant at that same point.

Introduction

The Kigali amendment to the Montreal Protocol came into force on 1 January 2019, with the aim of phasing down the production and consumption of hydrofluorocarbons (HFCs) and thus reducing so-called direct CO_2 emissions. However, actions to reduce the use of HFC refrigerants were already underway in most developed countries. In European Union, the F-gas Regulation was published in 2014, establishing restrictions on the use of HFC refrigerants according to their Global Warming Potential (GWP) and introducing the concept of quotas, which dictate the admissible production/import of HFCs to be progressively reduced to 93% (2016), 63% (2018), 45% (2021) and 21% (2030) compared to the average consumption in the period from 2009 to 2012. The reduction from 93 to 63% already led an increase in prices and a decrease in the availability of high GWP refrigerants such as R-410A or R-404A, driving the use of much lower GWP alternatives. In the United States, SNAP Rules 20 and 21 established by EPA (United States Environmental Protection Agency) prohibit the use of certain high-GWP HFCs as alternatives in different sectors such as refrigeration and air conditioning. Although both SNAP Rule 20 and Rule 21 were vacated by the USA Court of Appeals for the District of Columbia, some Climate Action states are taking action independently, proposing these regulations with minimum modifications. In Japan, the "Act on Rational Use & Proper Management of Fluorocarbons" classifies refrigerants according to their GWP and specifies the year these are banned for each application, which varies from 2018 for room air-conditioning to 2025 for condensing and refrigerating units. A similar regulation in Canada establishes bans according to the GWP of refrigerants from 2020 to 2025. As regards developing countries, in China for example the substitution of hydrochlorofluorocarbons (HCFCs) with natural refrigerants is recommended, although no concrete regulations are yet available.

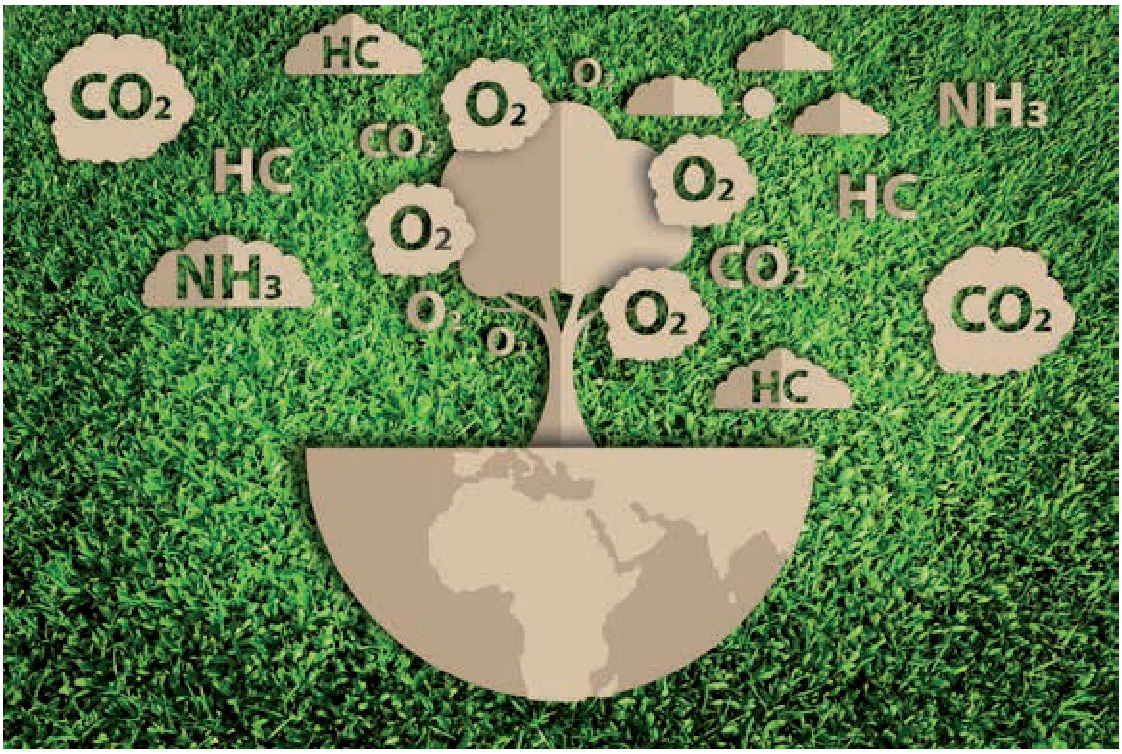
In this scenario, natural refrigerants and hydrofluoroolefins (HFOs) are being increasingly used worldwide. For example, HFO refrigerants R-452B and R-454B (together with the HFC R-32) are becoming more common in new HVAC direct expansion systems. However, their GWP is higher than 465, which make them a temporary solution. Other HFO refrigerants have a negligible GWP value, such as R-1234ze(E) (GWP=1), increasingly used in large chillers, or R-1234yf (GWP=4), currently used in the HVAC systems in new cars. These and likely new solutions in the near future are suitable options for certain applications and may be long term solutions, unless new research reveals a hazardous effect of HFOs on the environment or new regulations require them to be phased down or banned[1].

Natural refrigerants are considered a definitive solution due to their negligible GWP and zero effect on the environment, and technologies are evolving to optimise their use. In refrigeration, natural refrigerants have begun to be the preferred option in new equipment, especially in territories where HFC phase-down has started. R-744 was initially used in northern European Union countries where the climate conditions are more favourable, and now it is being increasingly used worldwide in new systems. R-717 (ammonia) is currently used in industrial refrigeration and will probably continue to be used in the future for the same applications. The use of R-290 (propane) for stand-alone units is growing and is expected to increase more after the update of national standards to the new IEC 60335-2-89, allowing a charge of 500 grams instead of 150 in commercial refrigeration appliances[2]. In HVAC units, R-290 is used where flammability requirements allow, whereas R-744 is being chosen for HVAC systems in vehicles. The extension of R-744 to other HVAC applications cannot be excluded. Practical examples of HVAC/R applications in which natural refrigerants are used are detailed in section 1 of this document.

[1] Detailed information on refrigerant regulations and trends can be found in the "Refrigerant scenario" white paper, available at https://www.carel.com/-refrigerant-scenario-white-paper.
[2] Additional information on flammability standards can be found in the "Flammable refrigerants: focus on hydrocarbons" white paper, available at https://www.carel.com/-flammable-refrigerants-focus-on-hydrocarbons-white-paper

Efficiency is another important subject of regulations nowadays, and impacts both the reduction of indirect CO_2 emissions and the electricity bill. In Europe, the Ecodesign and Energy Labelling Directives play an active part in the definition of new regulations for energy-using and energy-related products. Moreover, the energy conservation standards imposed by the Department of Energy (DOE) in United States cover most HVAC/R applications, from computer room air conditioners to refrigeration equipment. The scope is to significantly reduce the amount of energy consumed, through the use of available efficient technologies, and to consequently have a significant impact on the economy and environment. Similar regulations are active or are now emerging in other countries[3].

Many energy efficiency regulations for HVAC/R applications establish seasonal energy efficiency limits, thus taking into account the variations in outside air temperature over the year. This brings more precision to the procedure and more advantages from the use of variable speed technology, which is able to adapt energy consumption to the needs of the application. Modulating technologies help manage different operating conditions and adapt to different system requirements in the most optimum way, especially at part loads.



The combination of natural refrigerants and high efficiency leads to the search for new solutions. On one hand, the high operating pressures of R-744 and the transcritical state achievable at not very high temperatures has led to different configurations with new components, such as ejectors. On the other, the flammability of hydrocarbons and R-717 makes it essential to adopt specific safety measures. In summary, the aim of innovation is to obtain systems that are compatible with the unique characteristics of natural refrigerants and in line with regulations, without sacrificing efficiency.

This document is divided into four parts. Firstly, a summary of the characteristics of natural refrigerants. Secondly, an examination of the evolution of natural refrigerant cycles and the currently available possibilities. The last three sections describe examples of modulating technologies and high efficiency solutions. The objective is to have an overview of available technologies for designing a high-efficiency system when using natural refrigerants.

[3] Detailed information on energy efficiency regulations in Europe and the United States can be found in the "Ecodesign & Energy Labelling" and "USA: Commercial refrigeration equipment" white papers, available at https://https://www.carel.com/white-papers.

Natural Refrigerants

Natural refrigerants are substances that exist naturally in the environment. With zero ODP and very low or zero GWP, these are considered the definitive solution to the environmental damage caused by synthetic refrigerants.

The most widespread natural refrigerants used in HVAC/R applications today are carbon dioxide (CO_2, R-744), hydrocarbons such as propane (R-290), isobutane (R-600a) and propylene (R-1270), and ammonia (NH_3, R-717). These are widely available on the market at a very low price. Other natural refrigerants are water (H_2O, R-718) and air (R-729), used only for special applications, or sulphur dioxide (SO_2) and methyl chloride (CH_3Cl), which are no longer used.

The main characteristics of the most commonly-used natural refrigerants are summarised in the following table:

Refrigerant	ASHRAE number	Molecular formula	Safety group	GWP	ODP	Critical temperature (°C)	Critical pressure (bar)	Normal boiling temperature (°C)
Carbon dioxide	R-744	CO_2	A1	1	0	31.2	73.8	-79
Propane	R-290	C_3H_8	A3	3.3	0	96.7	42.6	-42
Isobutane	R-600a	C_4H_{10}	A3	4	0	135	36.5	-11.7
Propylene	R-1270	C_3H_6	A3	1.8	0	92.4	46.3	-48
Ammonia	R-717	NH_3	B2L	0	0	132.4	112.8	-33

*Safety group according to ASHRAE Standard 34. This standard classifies refrigerants according to their toxicity (A= non-toxic; B= evidence of toxicity) and flammability (1= no flame propagation; 2=lower flammability; 2L= mildly flammable; 3= higher flammability).

1. Carbon dioxide

Carbon dioxide (CO_2, R-744) is a colourless fluid, heavier than air at normal conditions and odourless at low concentrations. Being a non-flammable and non-toxic substance, it is classified as A1 according to ASHRAE Standard 34.

The effect of R-744 on the ozone layer is null, having an ODP value of 0. As regards its global warming impact, its GWP is 1, which is the reference value for comparing the direct impact of other refrigerants. However, it can be considered that R-744 does not contribute to climate change, as it is obtained as a by-product from industrial processes and would otherwise be emitted into the atmosphere, if not used in leak-free refrigerant circuit. Additionally, R-744 has an excellent coefficient of thermal transfer and extremely low viscosity, which reduces compressor power input.

The major challenge with R-744 arises from the fact that the critical point (T_C=31.2 °C, P_C= 73.8 bars) is easily attainable at a temperature that is common in many climates. This means that the system works in transcritical mode in certain conditions, which implies pressure and temperature are no longer related. Measures need to be adopted to keep these values under control, in order to optimise heat exchange and maximise efficiency. Moreover, operating pressures are very high, and this represents the biggest challenge for the components in the installation, such as compressors, valves and piping. In concrete terms, high pressure involves the need to fit the equipment with suitable components, often using stainless steel instead of copper, and adopt TIG welding rather than silver alloy braze-welding. Safety systems are also required, such as vent valves. Nonetheless, it should be also stressed that high pressure means smaller diameter pipes can be used, and both pressure drop and compression ratio are lower.

From a thermodynamic point of view, the pressure value is of no particular relevance. What is important, in fact, is that the R-744 cycle is the only one that in normal conditions can reach the transcritical state at the compressor discharge. This means that supercritical R-744 does not condense; indeed the heat exchanger that acts as condenser in traditional circuits is called a "gas cooler". The following P-H diagram represents the difference between a subcritical and a transcritical cycle from a thermodynamic point of view:

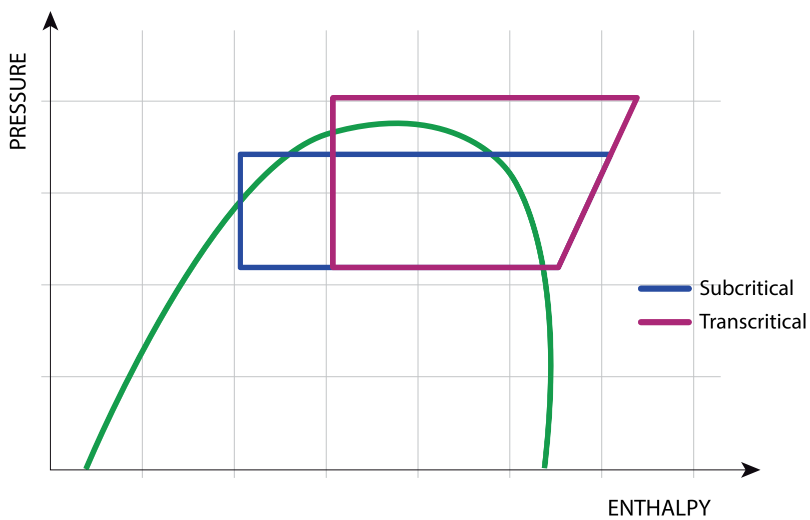


Fig. 1.a - P-H diagram of subcritical and transcritical R-744 cycles.

Recently, efforts have been focused on increasing efficiency of R-744 cycles, especially in warm climates. Parallel compressors and ejectors are some of the technologies that are now being applied. Additional details are described in the next section of this document.

As regards the applications in which R-744 is being used as an alternative to synthetic refrigerants, one of the most popular is supermarket refrigeration. Other applications include heat pump water heaters, commercial refrigerated vending machines, secondary expansion systems, industrial and transport refrigeration systems or vehicle air-conditioning systems.

2. Hydrocarbons

Hydrocarbons are odourless organic compounds made of nothing more than carbon and hydrogen atoms. They are flammable and non-toxic substances, and therefore their safety classification is A3 according to ASHRAE Standard 34. Their ODP of 0 and extremely low GWP values mean they are harmless to the ozone layer and in terms of global warming. Propane (R-290), isobutane (R-600a) and propylene (R-1270) are the most common hydrocarbons currently used in HVAC/R applications.

Hydrocarbons, unlike R-744, operate at standard working pressures, which means that the cycle is the same as in traditional systems. Their main strength is that they have excellent thermodynamic properties, giving high energy efficiency. For instance, the latent heat of vaporisation of hydrocarbons is almost two times higher than that of the most common HFC refrigerants (R-134a, R-404A and R-507): this means a higher cooling/heating effect for the same refrigerant mass flow.

The major challenge for the use of hydrocarbons as refrigerants is due to their high flammability. This requires a cautious design of the system and compliance with specific requirements for flammable refrigerants defined by standards.

Hydrocarbons are technically viable for small and medium-sized refrigeration and air-conditioning applications, as well as chillers. Applications include domestic fridges, beverage coolers, vending machines, industrial refrigeration, transport refrigeration, small air conditioning systems, chillers, heat pumps and water heaters.

3. Ammonia

Ammonia (NH_3, R-717) is an alkaline and colourless chemical compound at atmospheric pressure. Being a mildly flammable and toxic substance, it is classified as B2L according to ASHRAE Standard 34. R-717 is also corrosive, but its strong odour makes it easy to detect.

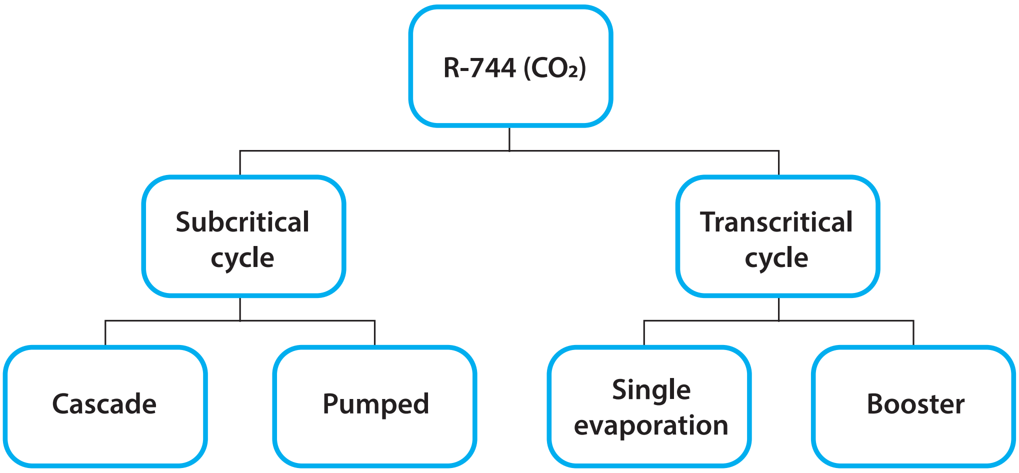
Regarding environmental impact, it does not have any harmful effect on the ozone layer and global warming when released into the atmosphere, thus its ODP and GWP values are 0.

R-717 is widely available on the market at a very low price. Working at standard operating pressures, its good thermodynamic properties, such as high latent heat of vaporisation, put it among the refrigerants with highest energy efficiency for both medium and low temperature operation.

However, the toxicity and flammability of R-717 have limited its use in public places. Many advances have been made recently to minimise risks for human health, such as the development of hermetically-sealed equipment and leak detection systems.
R-717 has mainly been used in industrial refrigeration for many years, however its use is being extended to other applications, such as commercial refrigeration as a secondary fluid.

Carbon dioxide systems

R-744 systems differ according to whether they are designed to work only below the critical point of CO_2 (T_C =31.2 °C, P_C = 73.8 bar) or also above that point. In essence, in a subcritical system the temperature of R-744 in the isothermal stage following compression of the fluid is below critical temperature, while in a transcritical system the temperature of R-744 at that stage (gas cooler outlet) is above 31.2°C. The different types of refrigeration and HVAC systems available for R-744 are shown in the diagram below, followed by details of each type.



1. Subcritical cycle

The simplest application of carbon dioxide as a refrigerant is in the subcritical cycle: R-744 is used in a secondary low temperature loop, either vapour compression (cascade system) or a pumped loop of liquid R-744 (pumped system). Basically, the P-H diagram of R-744 remains the same as for traditional refrigerants:

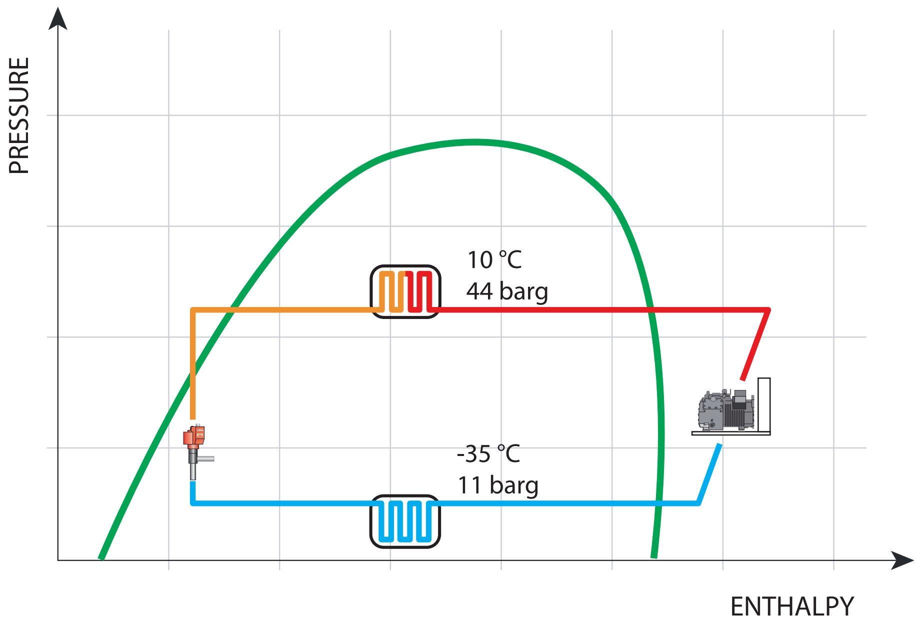


Fig. 1.a P-H diagram of subcritical R-744 refrigeration cycle.

Subcritical cascade system

In this type of system, there are two cycles. The primary cycle is managed using a refrigerant other than R-744 (typically R-134a, R-404A or R-717), whereas the second cycle is based on R-744. The two cycles are connected via one or more heat exchangers, normally plate exchangers, which allow the condensing temperature in the R-744 cycle to remain below the critical point, generally between -5 and -10 °C. Two different configurations are possible, depending on whether or not the primary cycle includes the medium temperature stage.

In the first configuration, the medium temperature stage is managed by the primary cycle, i.e. the one that uses a refrigerant other than R-744. The second cycle, based on R-744, comprises the low temperature stage. Common heat exchangers on one side condense the R-744 and on the other act as a normal evaporator for the medium temperature circuit. This means that the heat rejected by the condensing R-744 is absorbed by the evaporating refrigerant in the primary cycle.

It should be noted that, in the primary cycle, R-744 is condensed at the same time that cooling is provided to the MT showcases. To satisfy both requirements, pressure is variable.

An example of a cascade system, using R-134a in the primary cycle, is shown in the following diagram:

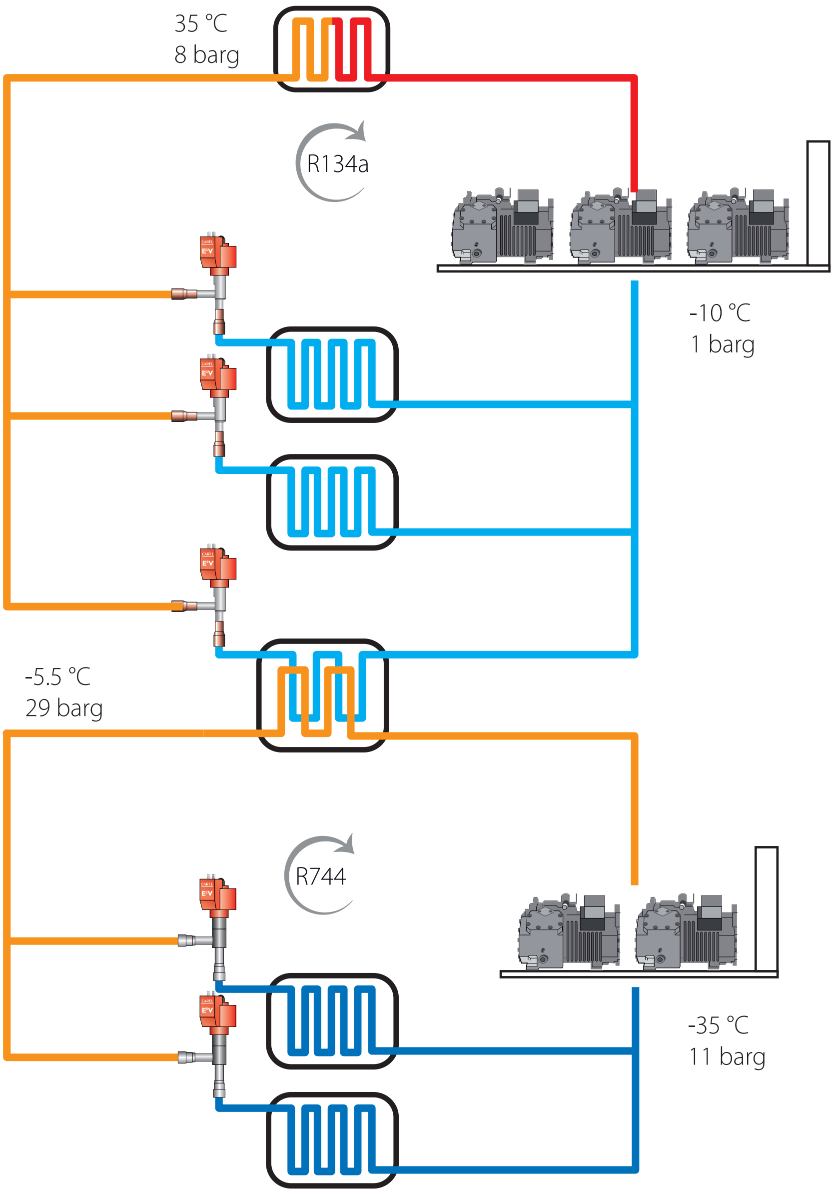


Fig. 1.b Scheme of subcritical R-744 cascade system using R-134a in the primary cycle.

Another configuration of cascade system consists in a primary cycle that is managed using a refrigerant other than R-744 and a secondary cycle that comprises both MT and LT circuits. Again, the two cycles are connected via one or more heat exchangers that on one side condense the R-744 and on the other act as normal evaporators:

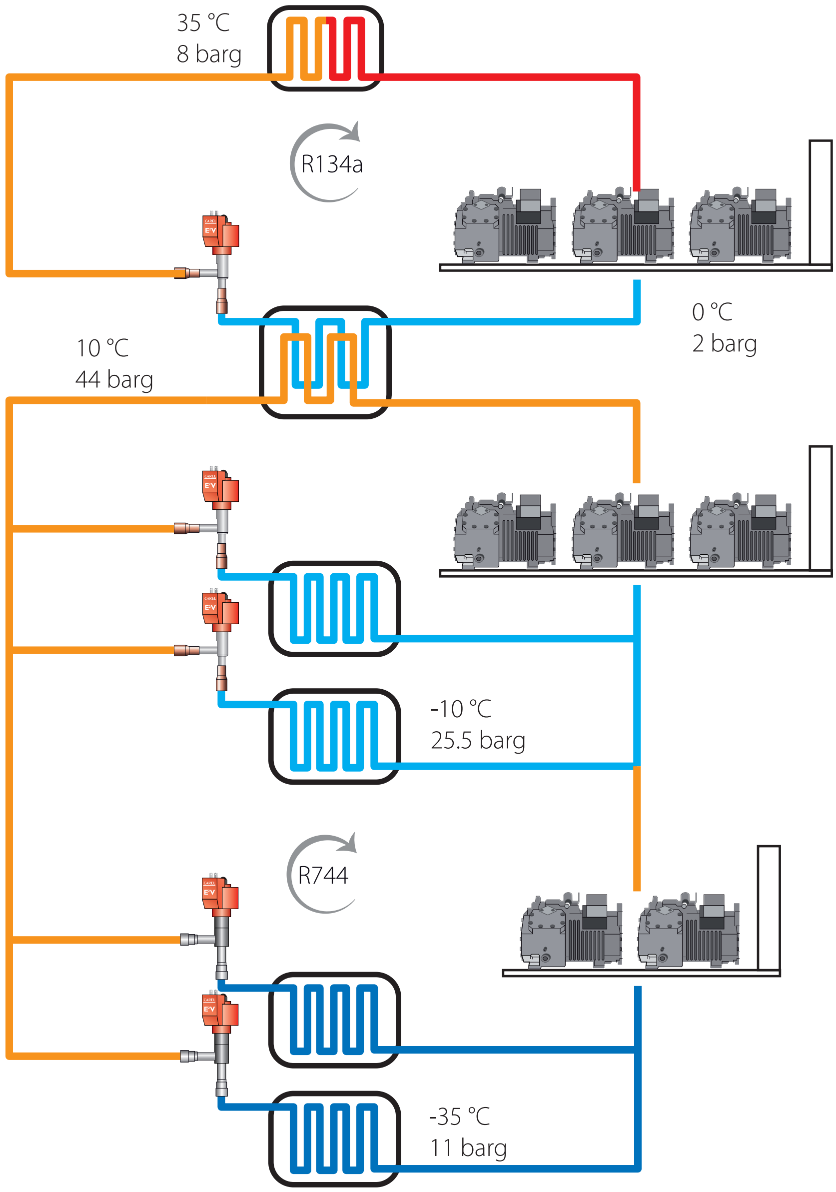


Fig. 1.c Scheme of subcritical R-744 cascade system using R-134a in the primary cycle and including both MT and LT circuits in the secondary cycle.

These types of configuration with R-134a in the primary cycle are allowed according to the current F-gas regulation (517/2014), even if an HFC refrigerant is used. In essence, the regulation specifies that fluorinated greenhouse gases with a GWP of less than 1,500 may be used in the primary refrigerant circuit of cascade systems. This is an exception to the ban on using fluorinated refrigerants with GWP greater than or equal to 150 in commercial multipack centralised refrigeration systems with a rated capacity greater than or equal to 40 kW from 2022.

Among the advantages of cascade systems, it is worth noting that the system is relatively similar to a traditional installation and operates at similar pressure (maximum 45 barg). System efficiency is even better than with standard HFC refrigerants and operation is the same in all climates.

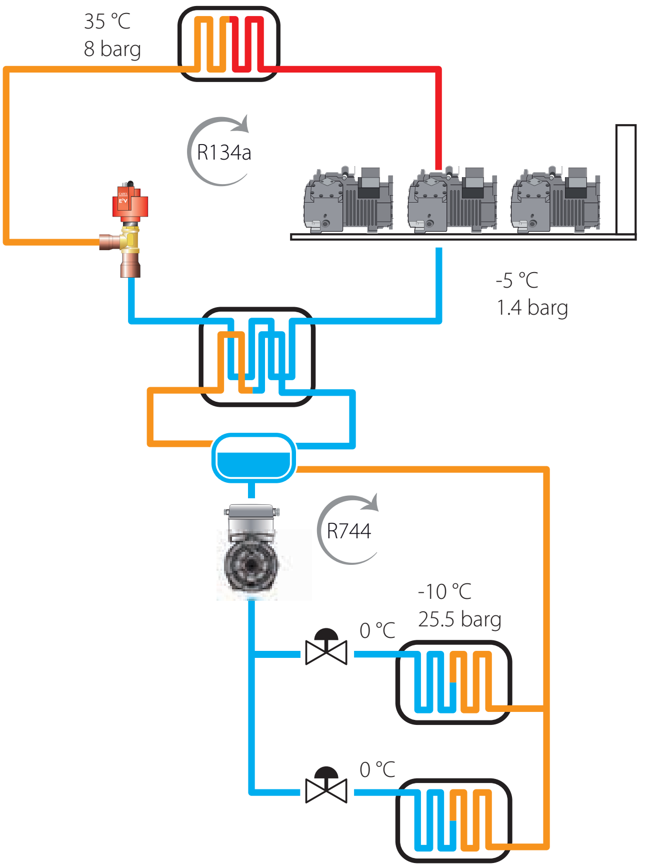
One drawback with respect to the other R-744 systems is the fact that the installation is not completely green, unless a natural refrigerant (usually R-717) is used in the primary circuit. When using R-717, however, flammability and toxicity limitations should be taken into account, much more restrictive if the primary cycle comprises medium temperature cabinets (first configuration).

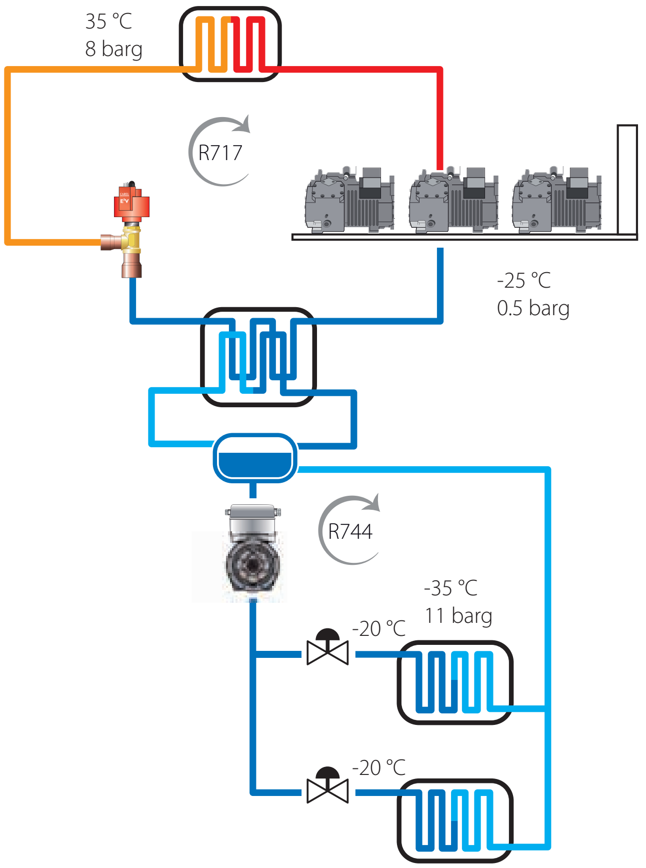
Subcritical pumped system

In subcritical pumped systems, there are two circuits. The primary circuit, typically a chiller using HFCs or HCs, has the task of cooling the liquid R-744 (normally through a shell and tube evaporator). R-744 is then pumped to be used as refrigerant for the low and/or medium temperature stages in the secondary circuit.

The difference with respect to traditional systems is the addition of pumps that circulate the liquid R-744 to the evaporators, where it is not expanded, but rather is simply superheated, returning to the receiver in the semi-liquid phase.

The following diagrams show three different possibilities for pumped systems. Both the diagrams below show pumped systems for only one stage, medium and low temperatures respectively, where R-744 is pumped. The diagram on the next page is a hybrid system, where the R-744 delivered to the MT cabinets is pumped, whereas the R-744 for the LT cabinets is compressed.





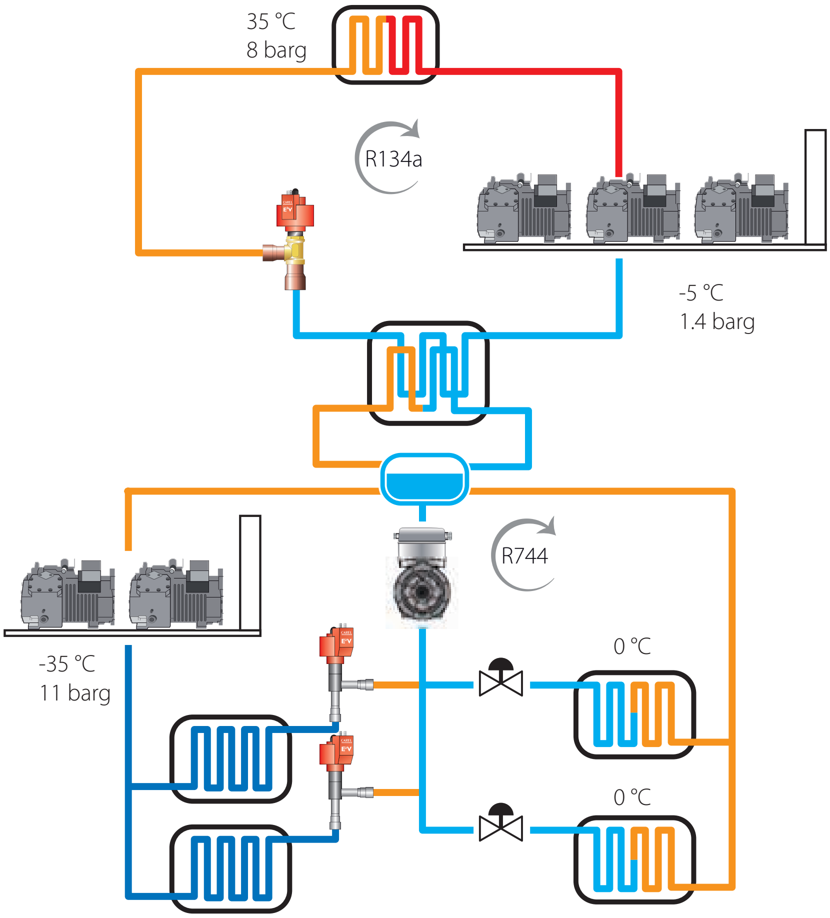


Fig. 1.d Schemes of three different examples of R-744 pumped systems.

The low synthetic refrigerant content, limited to the equipment room, is one of the strengths of these systems. Less restrictions on the use of R-717 or HCs, being outside of the store display area, facilitates their use, making the installation completely green.

However, the disadvantages of this kind of configuration have limited its use to just a few installations. Limitations include the additional pump energy consumption and the fact that is very sensitive to piping size. Furthermore, the additional heat exchange between the two refrigerants leads to higher temperature differences between evaporation and condensation, meaning the compressor needs to overcome higher pressure differences.

2. Transcritical cycle

The unique aspect of transcritical R-744 cycles is that in certain periods of the year, when the outside temperature is near or above the critical point of 31.2 °C, the system works in transcritical mode. The main difference compared to a traditional refrigeration cycle involves the stage in which the compressed gas is cooled, which does not correspond to constant condensing temperature, but rather changes continuously throughout the gas cooler, meaning temperature and pressure are correlated in a different way. This in turn means that R-744 in the gaseous state is not condensed via a heat exchanger but rather is cooled by a gas cooler, leaving it in the form of a dense gas.

As regards the efficiency of the cycle, gas cooler pressure control is essential. On one hand, pressure must not be too high, otherwise the system will shut down or the safety vent valves will be activated. However, the optimum pressure is not "as low as possible" as in the case of traditional circuits. This can be more easily explained using a P-H diagram, like the one shown below. In practice, for a given gas cooler outlet temperature (blue line), different cycles can be considered based on heat exchanger pressure. It can be seen that, starting from the cycle drawn in red and increasing the pressure, there is an increase in output that exceeds the increase in compression work: efficiency is therefore higher (cycle drawn in blue). On exceeding the cycle pressure shown in blue, the increase in compression work exceeds the increase in cooling capacity, meaning a reduction in efficiency (cycle drawn in violet). Optimising efficiency thus comes from maintaining the optimal pressure value during operation of the unit.

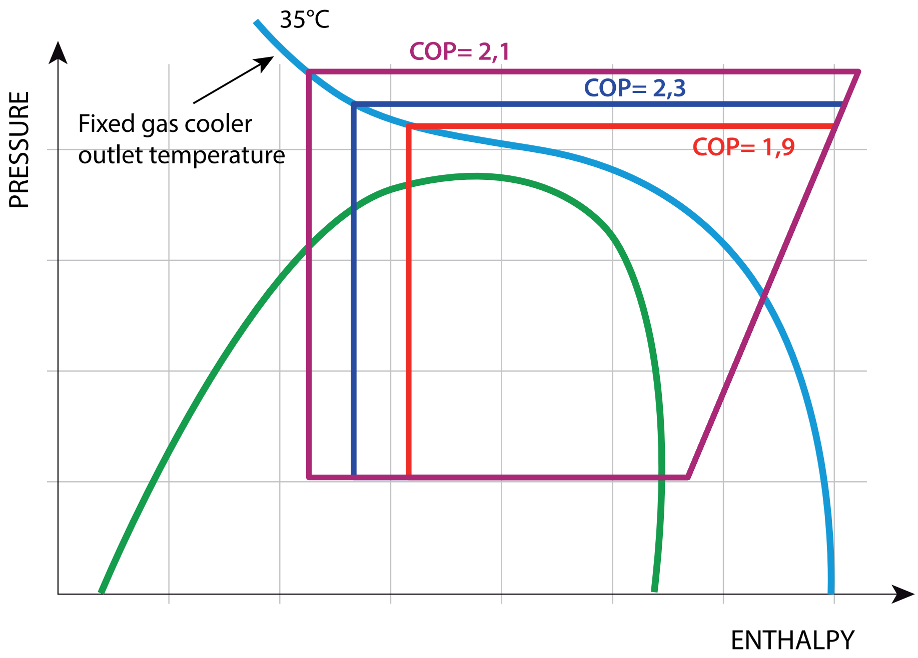


Fig. 2.a - P-H diagram of supercritical R-744 cycles with different values of COP.

A correlation for the optimal heat rejection pressure in terms of evaporation temperature and gas cooler outlet temperature has been reported[4]:

$$P_{opt} = (2.778 - 0.0157 \times T_{evap}) \times T_{gc} + (0.381 \times T_{evap} - 9.34)$$

where P_{opt} = optimal pressure, T_{evap} = evaporation temperature and T_{gc} = gas cooler outlet temperature.

The temperatures are in °C and the pressures are in bars.

Transcritical R-744 systems can be designed for single or double evaporation (booster).

Single evaporation

Single evaporation systems comprise just one compression stage, either low or medium temperature. The following diagram shows an example of this type of system, where only medium temperature evaporators are present.

[4] Liao, S.M, Zhao, T.S., Jakobsen, A., A correlation of optimal heat rejection pressures in transcritical carbon dioxide cycles, Applied Thermal Engineering, 20 (2000) 831-841.

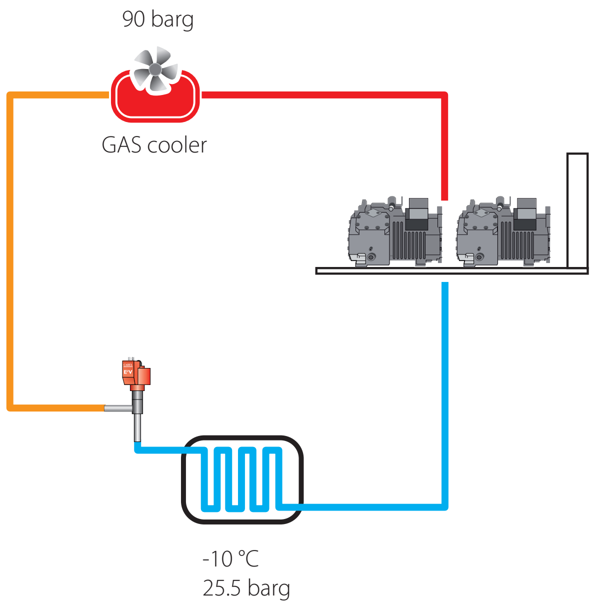


Fig. 2.b - Scheme of a single evaporation R-744 unit.

Booster

A booster system involves two compression stages of the same refrigerant, in this case R-744. The refrigerant discharged by the low temperature compressors flows, via an intercooler, to the suction port of the medium temperature compressors.

As shown in the following scheme, transcritical R-744 booster systems generally feature four sections with different pressures:

- high pressure: the section from the medium temperature compressor discharge to the EEV valve (in red);
- medium pressure: the section from the medium temperature evaporators downstream of the expansion valve to the suction side of the medium temperature compressors (in light blue);
- low pressure: the section from the low temperature evaporators downstream of the expansion valve to the suction side of the low temperature compressors (in blue).

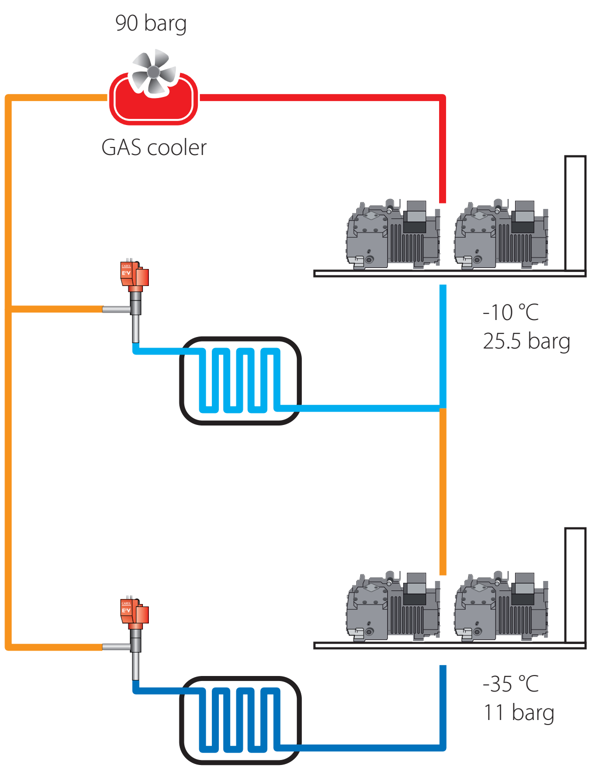


Fig. 2.c - Scheme of a booster R-744 system.

2.1. Energy saving technologies for transcritical CO_2 systems

Transcritical CO_2 cycles have evolved over recent years, leading as a result to different configurations that can be adopted depending on the climate conditions and other factors. The main different types of transcritical CO_2 cycles used so far for both single evaporation and transcritical CO_2 systems are described below. These are summarised in the following diagram:

	TRANSCRITICAL CO_2 CYCLES				
	Cycle 1: Traditional cycle	Cycle 2: Three valves	Cycle 3: Parallel compression	Cycle 4: Ejectors	Cycle 5: FTE
Energy saving options	Option 1: sub cooler				
	Option 2: evaporative cooling				
	Option 3: economizer				

Tab. 1.a Types of transcritical R-744 cycles.

For the sake of simplicity, the diagrams represented are "single evaporation" (except FTE and economizer), but all of the options can also be applied to booster systems.

Cycle 1: traditional circuit

The simplest implementation of a transcritical R-744 refrigerant circuit is the traditional circuit used for any other refrigerant. This involves a compressor, an expansion element and two heat exchangers, one of which an evaporator and the other that acts as a gas cooler/condenser.

The simplicity of this diagram compared to those that follow makes it the most economical. Always bearing in mind however that the ability to withstand high pressure costs more than circuits that use other refrigerants.

One of the main drawbacks is low efficiency. Indeed, as only one control valve is available, it is not possible to obtain both optimal gas cooler pressure control and superheat control at the evaporator outlet at the same time. The valve is used to manage one or the other but is not able to optimise both heat exchangers. Furthermore, the change in enthalpy of vaporisation (cooling capacity) is only slightly higher than the compression work (power consumption).

This type of circuit is used for low capacity units.

Here below, the P-H diagram and the scheme of R-744 traditional circuit are represented:

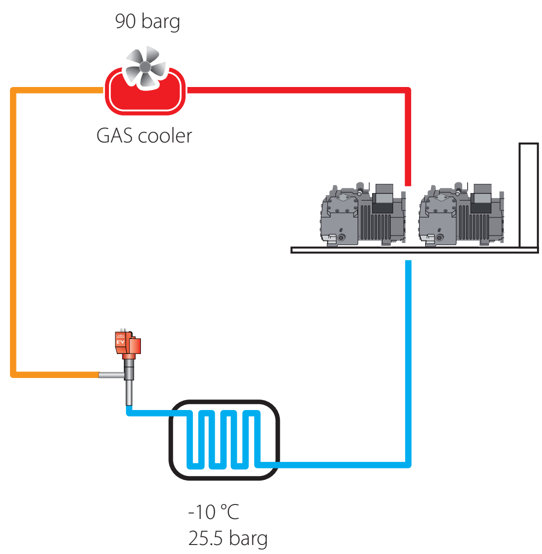


Fig. 2.e - Scheme of a traditional transcritical R-744 system

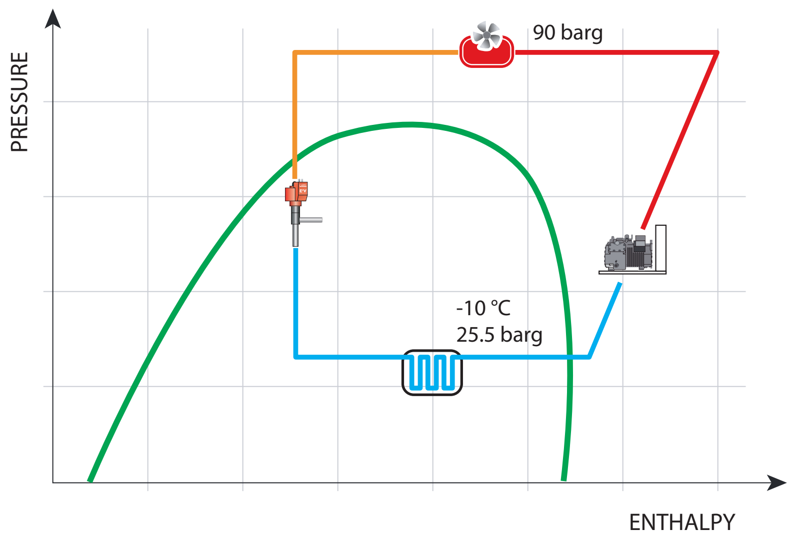


Fig. 2.f - P-H diagram of a traditional transcritical R-744 system

Cycle 2: three valves

The diagram shown in cycle 1 can be improved to achieve simultaneous control of gas cooler pressure and evaporator superheat. The following components need to be added:

- a high pressure valve (HPV) that controls the gas cooler pressure
- a receiver that decouples the flow in the HPV valve from that in the expansion valve
- a receiver pressure regulating valve (RPRV or flash gas valve), which draws gaseous refrigerant directly into the compressor suction pipe when the work done independently by the other two valves causes the pressure to rise too much.

The resulting circuit is thus capable of simultaneously optimising the operation of both heat exchangers. Furthermore, the refrigerant taken from the tank to the expansion valve is in the saturated liquid state, with low enthalpy, and this considerably increases the cooling capacity of the evaporator. The procedure is easy to understand: from the receiver, the required liquid flows to all of the showcases, where is expanded by the expansion valves, whereas the excess refrigerant in the receiver is expanded by the flash valve gas; both gas flows are subsequently remixed before being compressed.

With respect to option 1, this diagram has two extra valves and a tank, which means higher costs, but also higher efficiency and better control of operating conditions.

The limitation of this cycle is that the refrigerant flow handled by the compressor is delivered back to the compressor itself via the flash gas valve. This is in fact a dissipative bypass, a waste of energy needed to keep the tank pressure under control. Consequently, even though efficiency is higher, it is still not optimal.

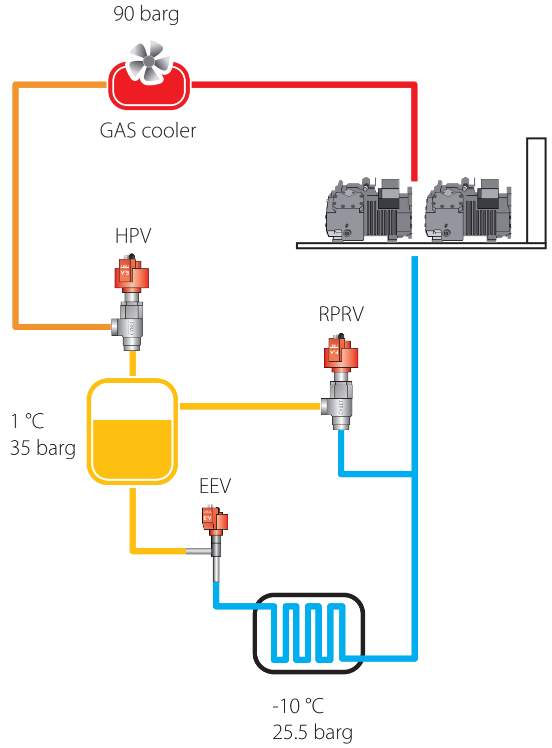


Fig. 2.g - Scheme of a three valves R-744 transcritical system

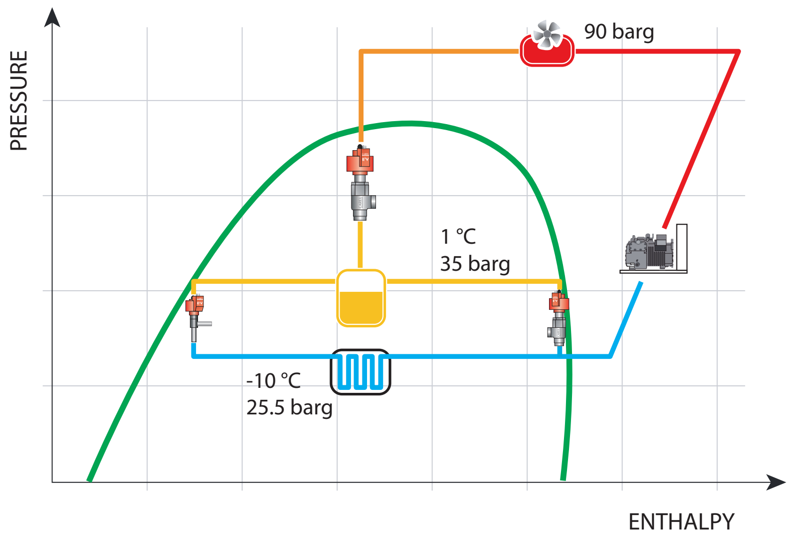


Fig. 2.h - P-H diagram of a three valves R-744 transcritical system

Cycle 3: parallel compression

The use of an additional suction line, called intermediate or parallel, improves energy efficiency when working in transcritical conditions, which makes this solution particularly suitable for milder climates. A bypass ensures that the R-744 coming from the receiver is no longer expanded before being delivered to the medium temperature compressor suction port, but rather flows directly to the suction port of the compressors in the parallel line. Synchronised management of the bypass valve and parallel compression increases system efficiency when the system is operating in transcritical conditions, drastically diminishing the amount of bypassed gas on the suction side and guaranteeing perfect receiver pressure control.

This type of diagram is appropriate for units with a relatively high cooling capacity that are usually equipped with two or more compressors.

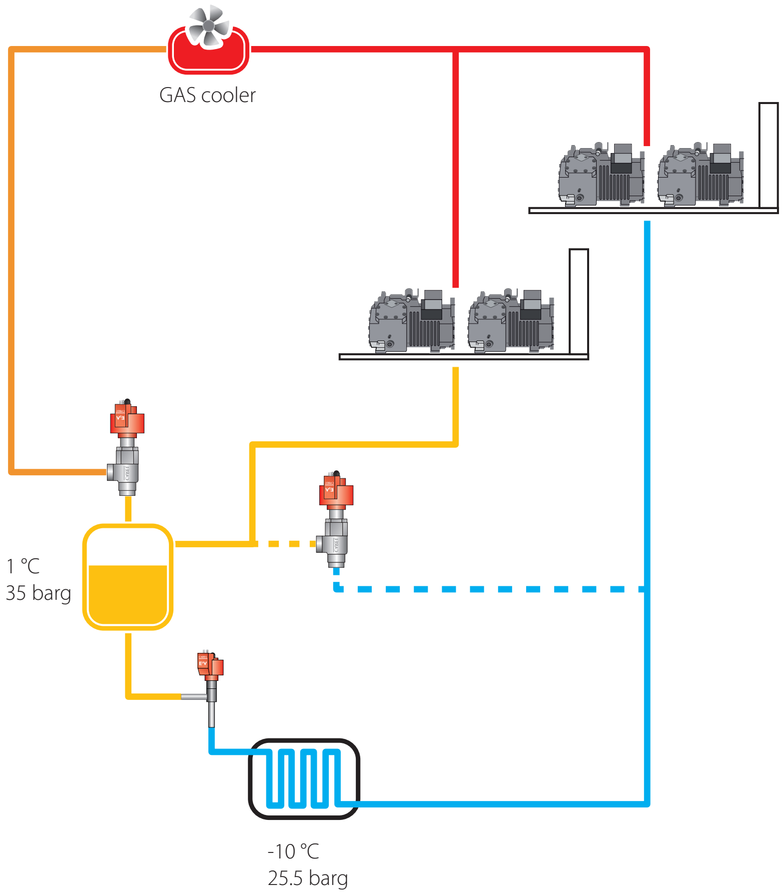


Fig. 2.i - Scheme of a R-744 transcritical system with parallel compression

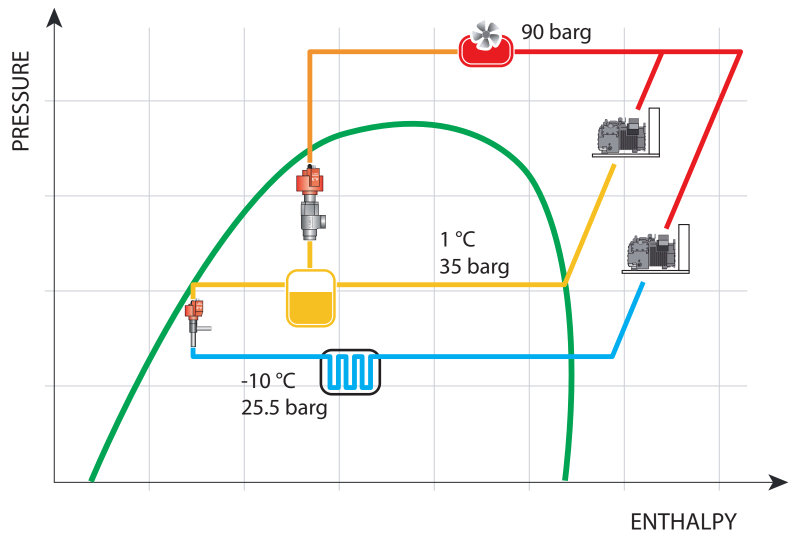


Fig. 2.j - P-H diagram of a R-744 transcritical system with parallel compression

Cycle 4: ejector

This diagram is based on a different assumption and exploits a special device: an ejector. The basis is that it takes advantage of the main characteristic of this refrigerant, i.e. the high pressure that is created in the gas cooler. In simple terms, an ejector is a device capable of using the potential energy of the high pressure refrigerant to draw in low pressure refrigerant and bring it to an intermediate pressure.

Ejectors can be classified by the nature of the flow as either vapour or liquid ejectors. The main difference is that liquid ejectors work with zero K superheat evaporators and a liquid separator is needed to collect the liquid. Evaporators need to be redesigned for higher evaporation pressures and lower superheat values[5] in order to avoid a reduction in efficiency and the formation of ice.

As regards the cycle with ejector, the suction that takes place reduces the compression ratio and the flow-rate handled by the compressor, thus requiring less power consumption. Indeed, only the bypassed mass flow rate is compressed.

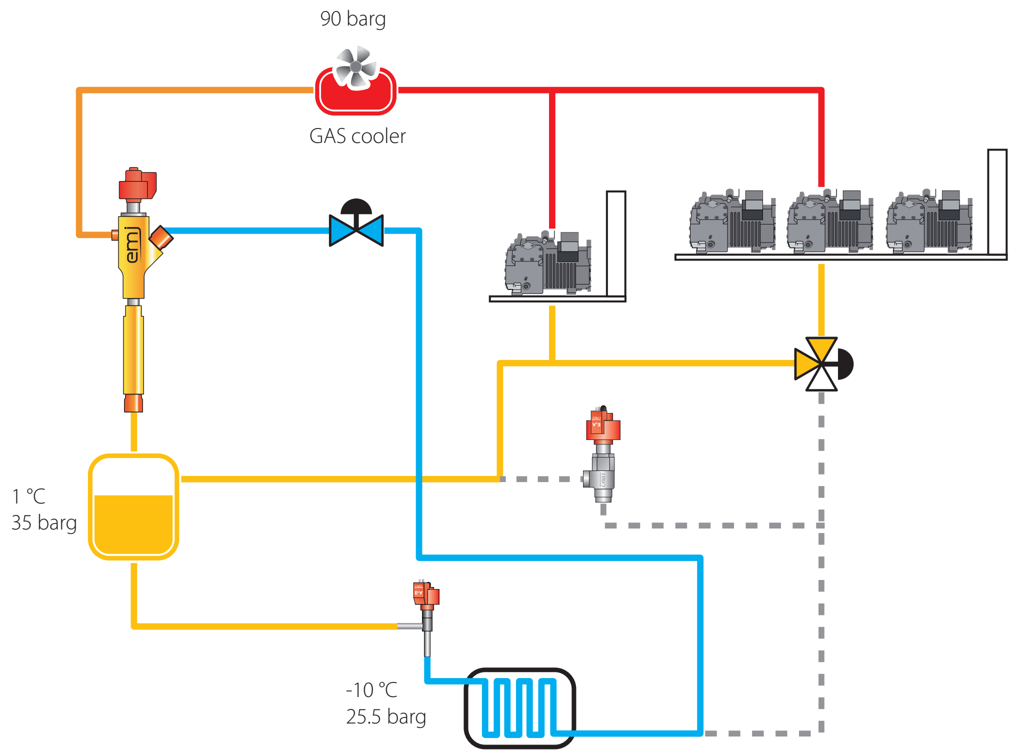


Fig. 2.k - Scheme of a R-744 transcritical system with ejector

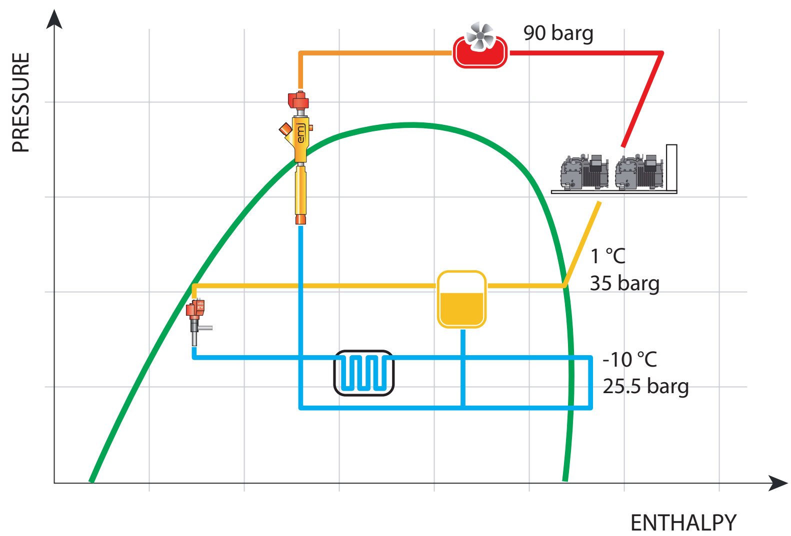


Fig. 2.l - Diagram of a R-744 transcritical system with ejector

This mode, called "ejector mode", is only activated in high pressure conditions. In all other conditions, the cycle works with the main and parallel compressors and expansion valves, including the ejector itself (which works as a HPV valve), as in the previous diagrams.

[5] Hafner, A., Nekså, P., Hemmingsen, A.K.T., Latest energy efficiency achievements within R744 refrigeration, Industria & Formazione (2012) 32-36.

Cycle 5: Full Transcritical Efficiency (FTE)[6]

This solution consists in adding to cycle 2 a multilevel liquid receiver that collects the liquid coming from the MT evaporators, which are designed to work as zero K superheat evaporators to ensure that the refrigerant is in the liquid state. Electro-mechanical sensors in the liquid receiver control the level of liquid as follows: when there is enough liquid, it is delivered to the low temperature evaporators; (this allows to increase the enthapy differential in the low temperature evaporators) however, when the multilevel liquid receiver is nearly empty, the liquid delivered to the low temperature evaporators comes from the main receiver. In this configuration, flash gas flows to the inlet of the multilevel liquid receiver instead of the MT compressors, collecting the droplets of liquid inside it.

This type of cycle is suitable only for booster systems.

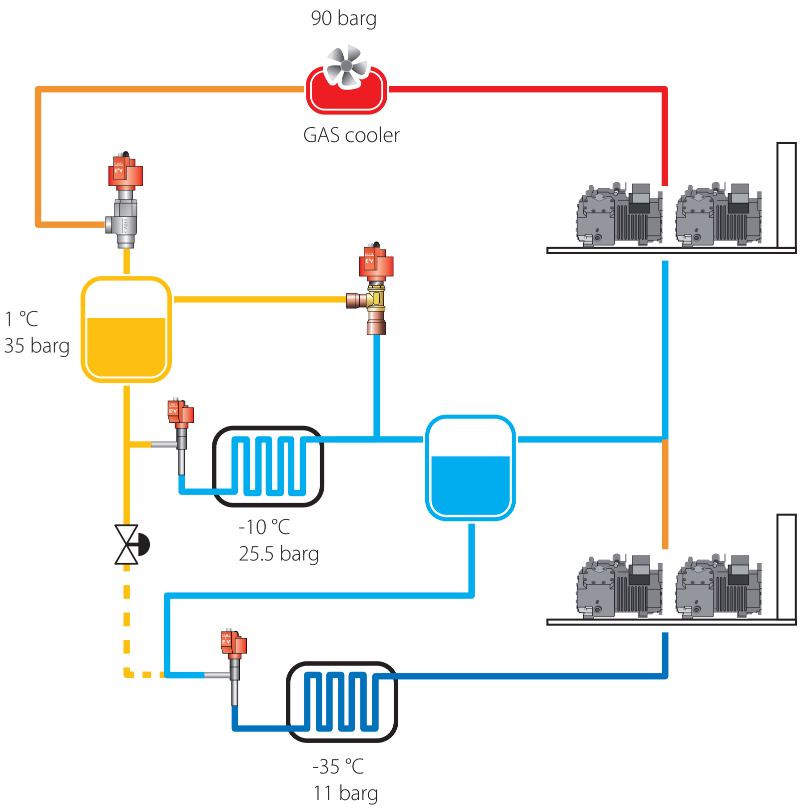


Fig. 2.m - Scheme of a R-744 transcritical system with FTE

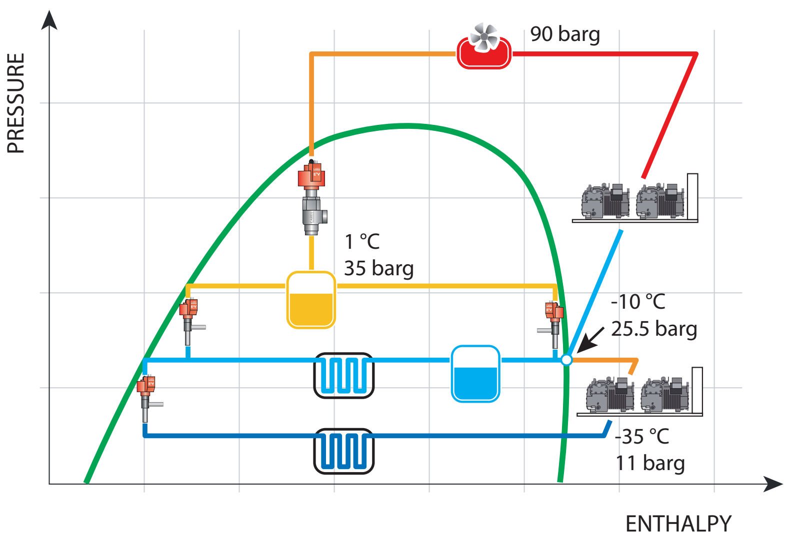


Fig. 2.n - P-H diagram of a R-744 transcritical system with FTE

[6] https://www.proinstalaciones.com/articulos/tecnico/2738-instalaciones-transcritas-de-co2-con-fte

Option 1: subcooler

The function of a subcooler is to exploit the gas temperature after expansion in the flash valve to subcool the liquid refrigerant before the EEV. Consequently, the enthalpy differential in the evaporator is higher and thus more cooling is "produced".

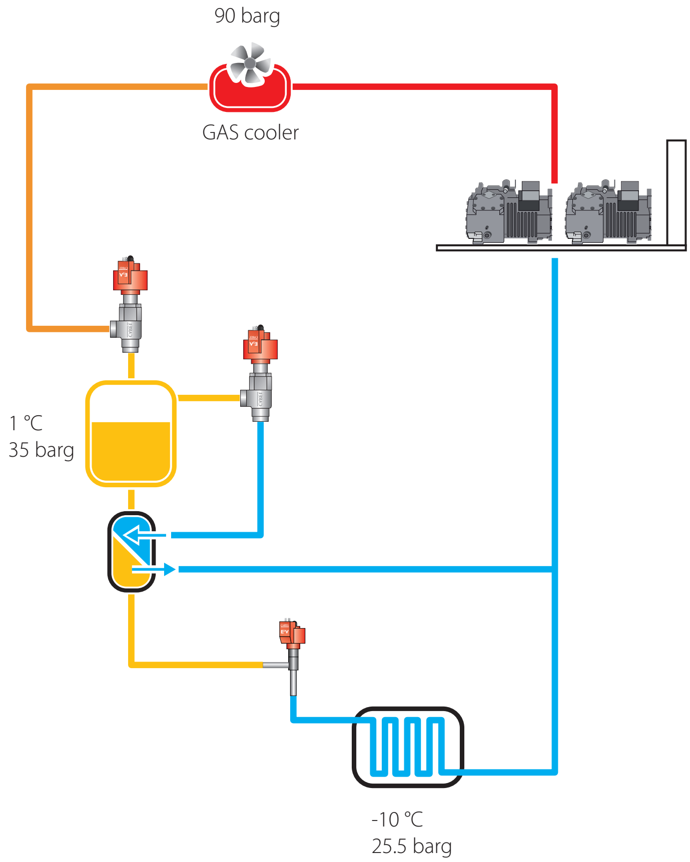


Fig. 2.o - Scheme of a R-744 transcritical system with subcooler

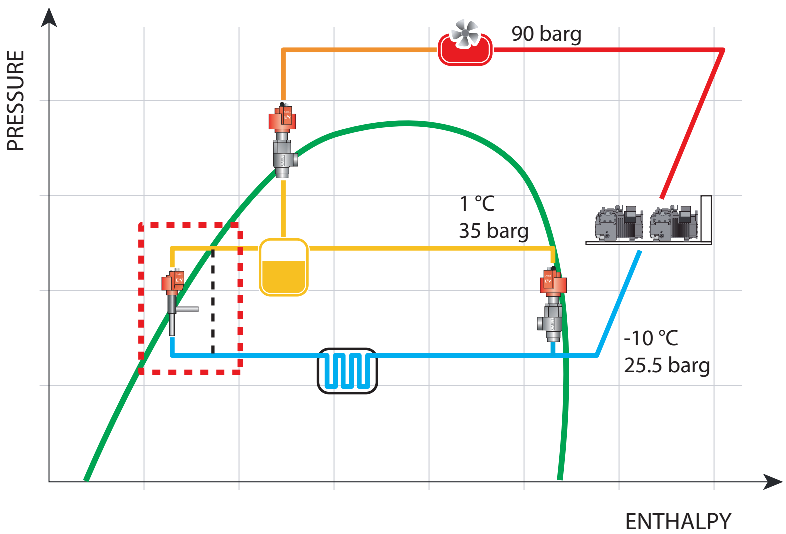


Fig. 2.p - P-H diagram of a R-744 transcritical system with subcooler

Option 2: evaporative cooling

The objective of evaporative cooling in R-744 refrigeration systems is to reduce the temperature of the gas cooler by spraying micro particles of water, bringing significant energy savings due to the reduction of power consumed by the compressor. The coils are wetted so as to exploit the evaporation of water from their surface. This solution is especially suitable to increase the efficiency of R-744 systems in warm climates.

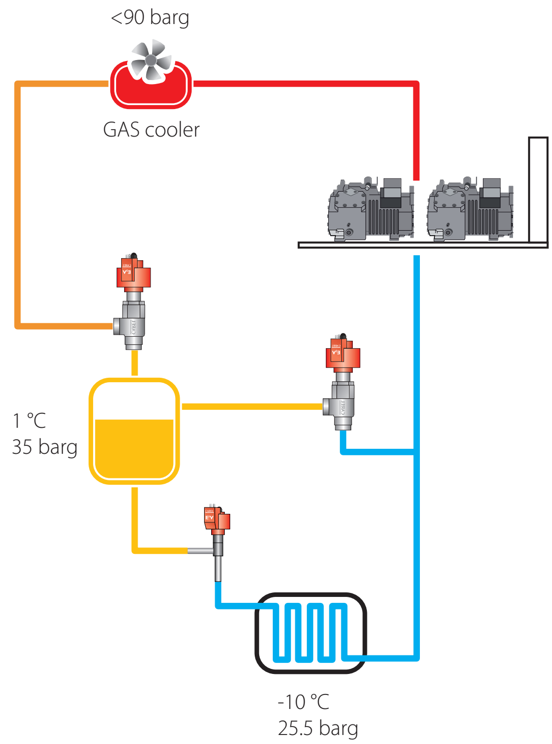


Fig. 2.q -Scheme of a R-744 transcritical system with evaporative cooling

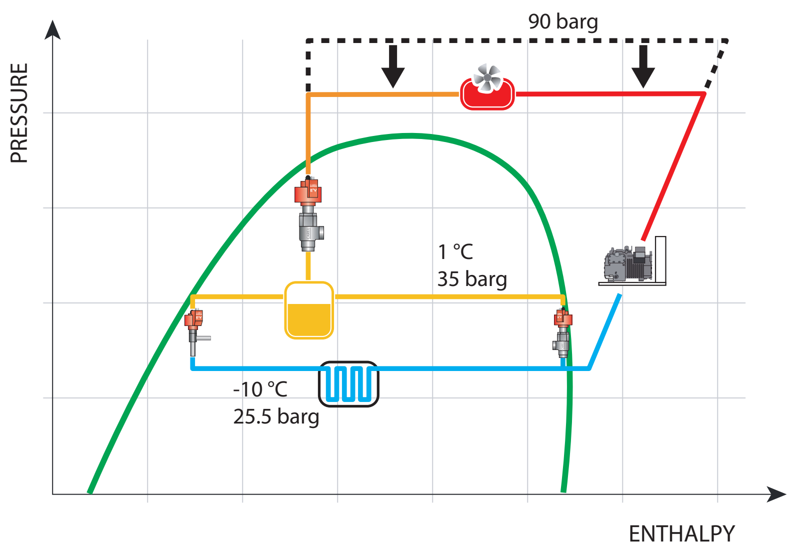


Fig. 2.r - P-H diagram of a R-744 transcritical system with evaporative cooling

There are two types of evaporative cooling: direct and indirect. Direct evaporative cooling implies that air is humidified, whereas with indirect evaporative cooling, the air is kept separated from the process of evaporation and, therefore, it is not humidified. In R-744 systems, direct evaporative cooling is used.
Specific information on CAREL's evaporative cooling solutions can be found in the penultimate section of this document.

Option 3: economizer[7]

The use of economizers is a technique that aims to reduce the temperature at the gas cooler outlet in order to improve the energy efficiency of transcritical R-744 cycles. To do so, a flow of R-744 extracted from another point in the system and expanded through an expansion valve. In practice, an economizer is another type of subcooler.

As shown in the following diagram, the economizer cools the refrigerant leaving the gas cooler via a flow of refrigerant drawn and expanded from the gas cooler outlet. The expanded fluid has low vapour quality; thus, the cooling capacity to reduce the temperature of the high-pressure flow is greater than that of other cooling systems that reduce the temperature with the vapour extracted from the liquid receiver.

The example shown here below involves an R-744 two-valve cycle.

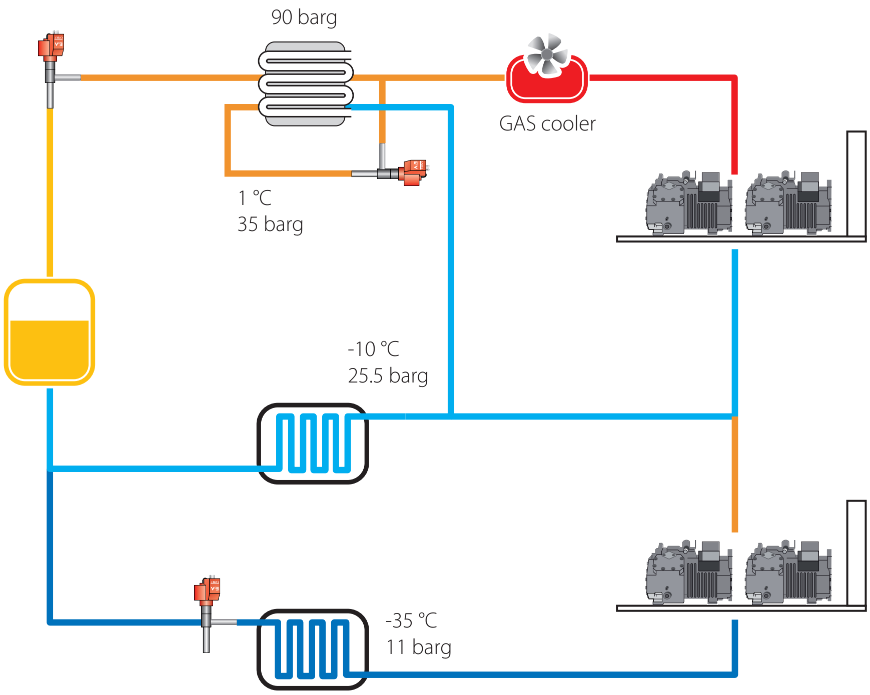


Fig. 2.s - Scheme of a R-744 transcritical system with economizer

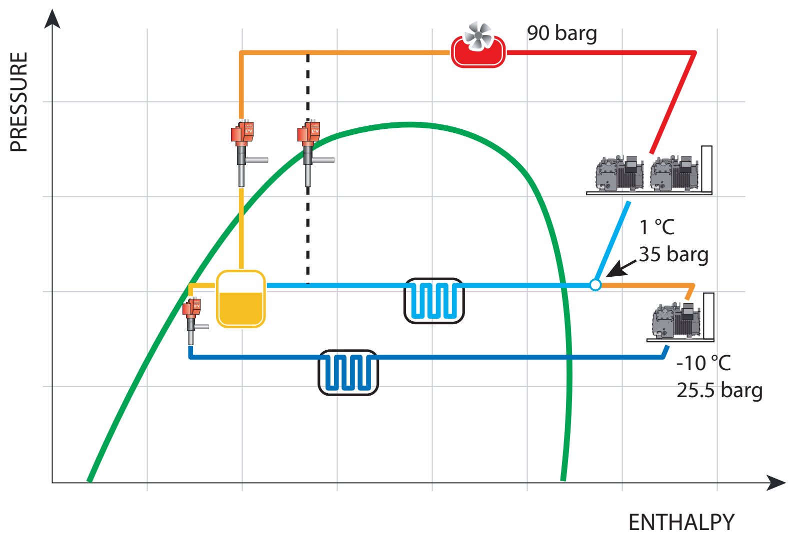


Fig. 2.t - P-H diagram of a R-744 transcritical system with economizer

[7] Catalán-Gil, J., Nebot-Andrés, L., Sánchez, D., Llopis, R., Cabello, R., Calleja-Anta, D., Improvements in CO_2 Booster Architectures with Different Economizer Arrangements, Energies 13 (2020) 1271.

Hydrocarbon systems

Hydrocarbons are easily implemented in conventional cooling systems, requiring minimal investment in components and design. However, as explained in the introduction, systems with hydrocarbons are subject to international safety guidelines and legislation due to the high flammability of these types of refrigerants, which has led to the development of a multi-circuit system. Further details are explained below.

1. Single circuit

This involves a traditional circuit with one compressor, one condenser, one expansion valve and one evaporator. This configuration can be used for medium or low temperature systems.

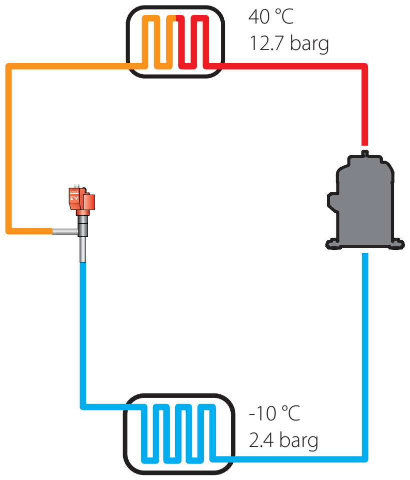


Fig. 1.a - Scheme of a R-290 system (single circuit)

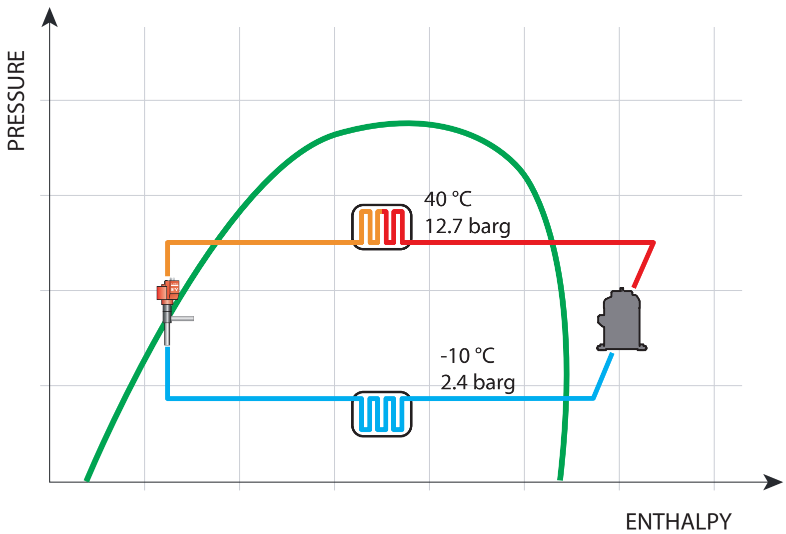


Fig. 1.b - P-H diagram of a R-290 system (single circuit)

2. Multi-circuit

The idea of this type of configuration emerged as a result of the maximum charge limit for refrigeration appliances using flammable refrigerants, which in accordance with to IEC 60335-2-89 was 150 grams until 2019, making it necessary to find a solution for systems with a higher charge. Currently, even if the standard includes refrigeration systems with charges of up to 500 grams, it is expected that this type of configuration will still be used. On one hand, national standards have not been yet updated to the new international version approved in 2019, and the process will take several months. On the other, it remains to be seen whether additional requirements for systems with more than 150 grams of hydrocarbons are a barrier for the adoption of single circuits with high charges.

An example of this configuration can be seen in the following figure. Multi-circuit means more than one circuit, usually three, with one compressor and one expansion valve for each. Heat exchangers are common for all the circuits.

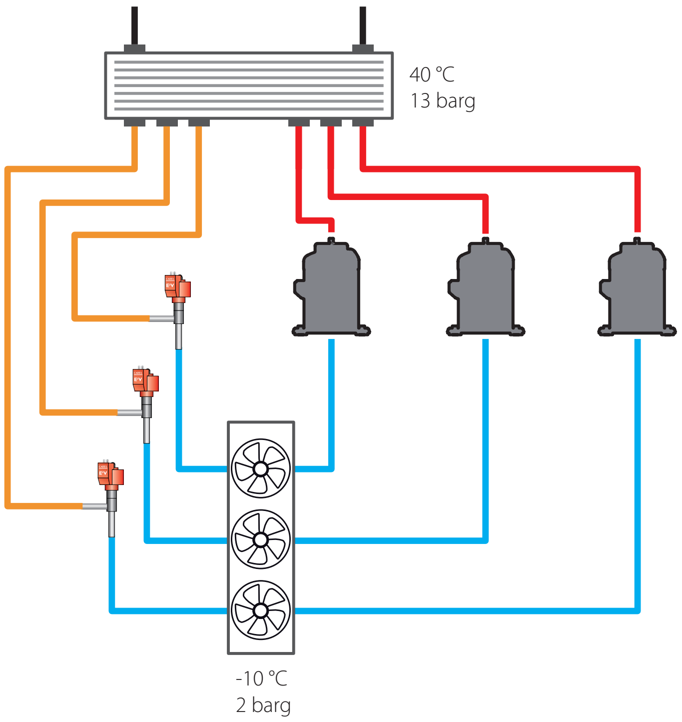
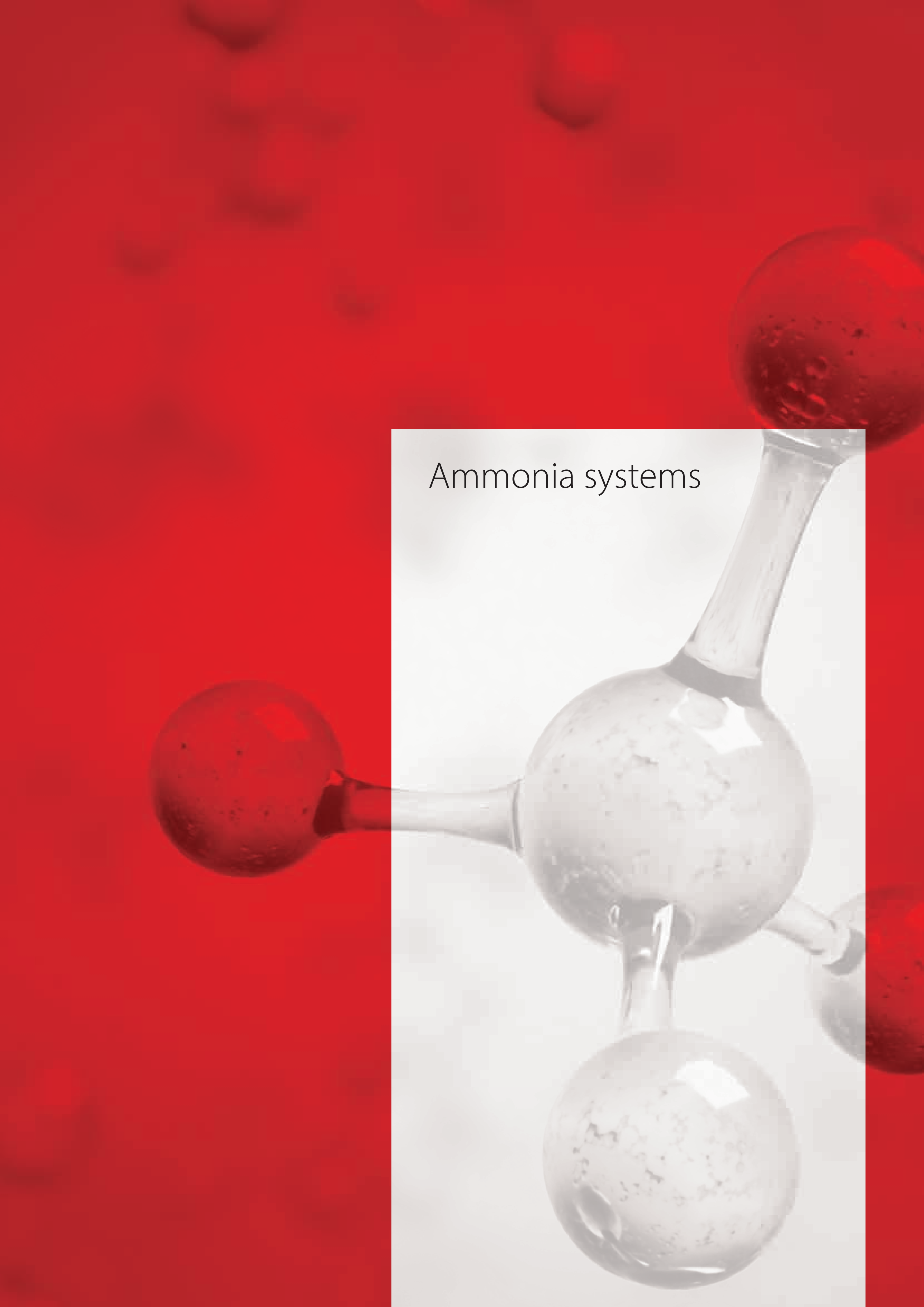
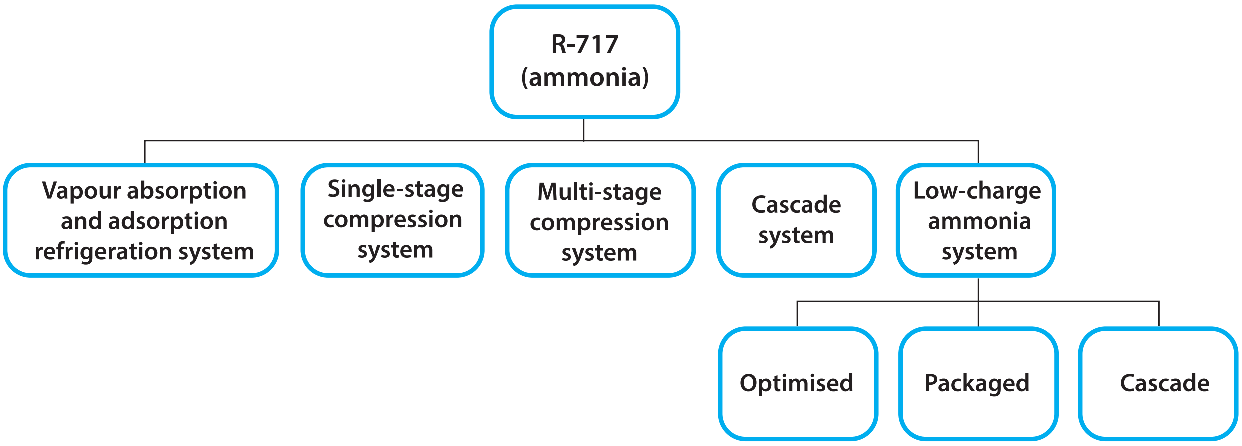


Fig. 2.a - Scheme of a R-290 system (three circuits)

Ammonia systems



There are different types of systems that can be used with R-717 as refrigerant and have been successfully implemented on the market:



The details are described below.

1. Vapour absorption and adsorption refrigeration systems

The vapour absorption refrigeration system based on ammonia-water is one of the oldest refrigeration systems. It exploits the fact that substances absorb heat when changing state from liquid to gas, just like the vapour compression cycle. In this case, however, the cycle is physically based on the capacity of some substances to absorb another substance in the vapour phase.

A simple absorption refrigeration system consists of an absorber, a pump, a generator and a pressure reducing valve. These components replace the compressor in a vapour compression refrigeration system. The other components in the cycle are the same: condenser, evaporator and expansion valve. In the absorption refrigeration system, ammonia is used as the refrigerant and water is the absorbent.

The diagram of a typical vapour absorption refrigeration system is illustrated in the following figure. Starting from the evaporator, the low pressure ammonia vapour refrigerant passes through a heat exchanger and enters the absorber, where is absorbed by the cold water. The absorption of ammonia vapour by water lowers the pressure in the absorber and raises the temperature of the solution. A secondary cooling fluid (usually water again) is employed in the absorber to remove heat from the water-ammonia solution, needed to increase the absorption capacity of the water. Then, the mixture formed in the absorber is pumped to the generator by the liquid pump, increasing the pressure up to 10 bars. In the generator, the mixture is heated by an external source, such as gas, steam or solar energy. During the heating process, the ammonia vapour is released from the mixture in two ways: the weak ammonia solution flows back to the absorber at low pressure after passing through the pressure reducing valve, whereas the high pressure ammonia vapour from the generator is condensed in the condenser after passing trough the dephlegmator. The function of the dephlegmator is to reduce the concentration of water vapour at the exit of the generator. Liquid ammonia from the condenser goes to the expansion valve through the receiver and then to the evaporator.

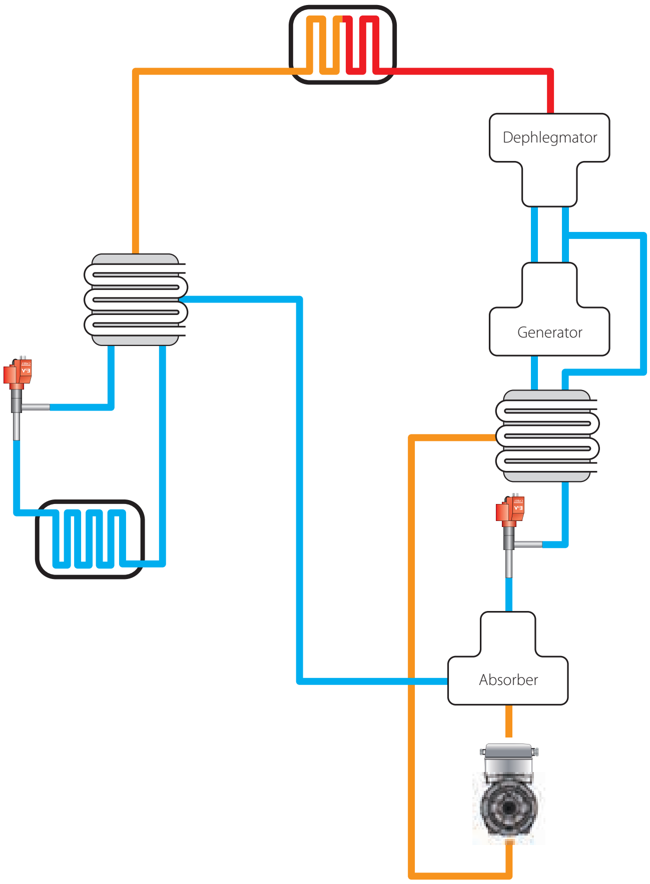


Fig. 1.a - Scheme of a R-717 vapour absorption refrigeration system

Adsorption refrigeration is very similar to absorption refrigeration. The difference is that the refrigerant or adsorbate vapour molecules adsorb onto the surface of a solid rather than a liquid. This implies that the operating characteristics are significantly different. Zeolite, alumina, silica gel and activated carbon are among the most common adsorbents used in these types of systems.

2. Single-stage compression system

This configuration comprises the components of a traditional refrigeration system, as well as a pump and a liquid separator, as shown in the following diagram.

Looking at the diagram, it can be seen that the high pressure liquid refrigerant flows from the condenser to the expansion valve, which regulates the pressure and delivers liquid refrigerant to the liquid separator. From there, the refrigerant in the liquid state, is pumped to the evaporator and then back to the separator. This ensures that the compressor does not receive any liquid. The refrigerant in the form of vapour at low pressure rises up and drawn back into the compressor before repeating the entire cycle again.

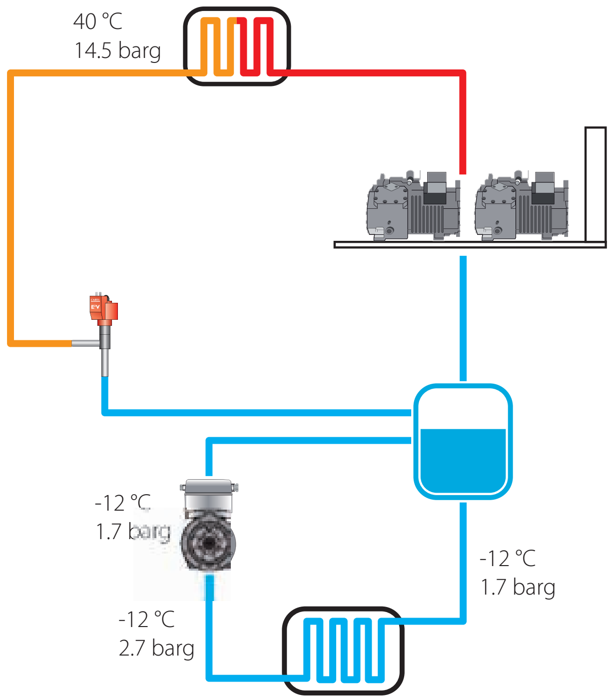


Fig. 2.a - Scheme of a R-717 single-stage refrigeration system

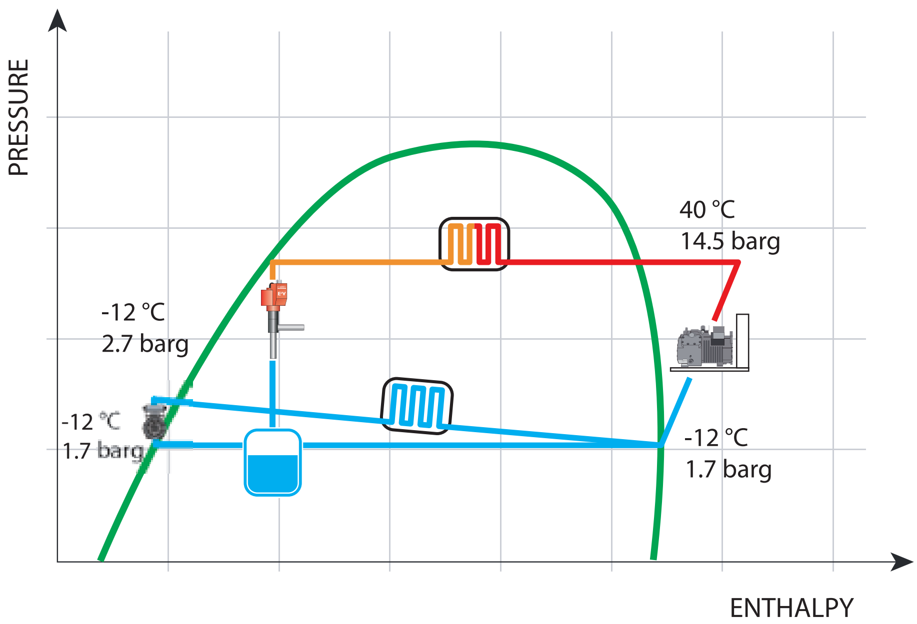


Fig. 2.b - P-H diagram of a R-717 single-stage refrigeration system

3. Two-stage compression system

This is the next evolution of the industrial refrigeration system, suitable for low temperature refrigeration applications, providing high efficiency and low compressor discharge temperatures. In this type of system, there are two compression stages, as the name implies. There is also a tank, called an intermediate cooler, between the receiver and the expansion valve.

Looking at the diagram below, it can be seen that there is a coil inside the tank, where the main refrigerant flow passes through before entering the main expansion valve. The refrigerant continues its flow via the separator, the evaporator and back to the separator.

Another refrigerant flow comes out of the main line and is sprayed into the tank via an expansion valve to produce a cooling effect: as it is sprayed and evaporates in the tank, it cools the submerged coil. This sub-cools the main refrigerant flow inside the coil before this reaches the main expansion valve. The vapour refrigerant drawn out of the separator flows to the low-stage compressor to increase its pressure. From there, it flows into the intermediate cooler, which helps condense the refrigerant. The vapour refrigerant is drawn out of the intermediate cooler and flows to the high-stage compressor, before flowing into the condenser and repeating the entire cycle.

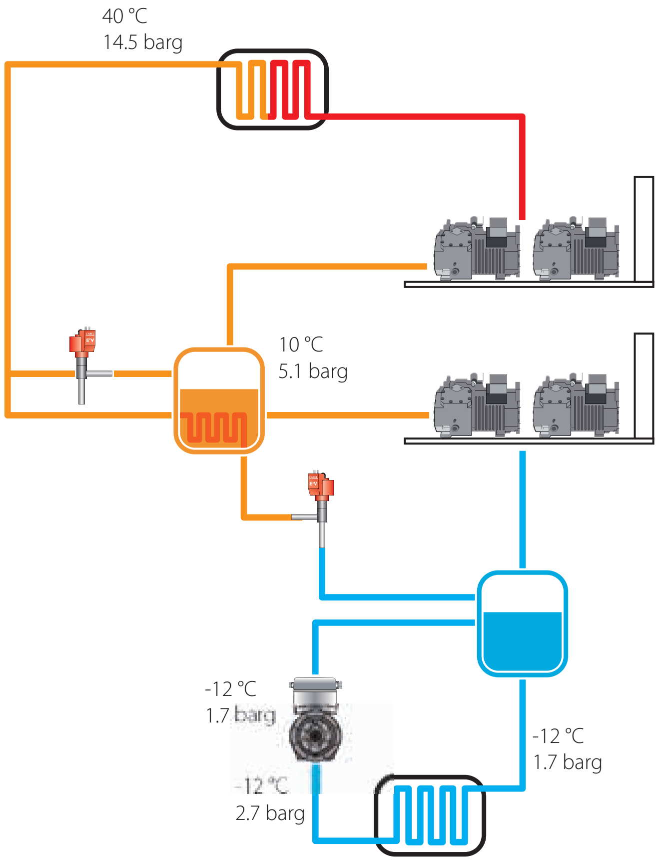


Fig. 3.a - Scheme of a R-717 two-stage refrigeration system

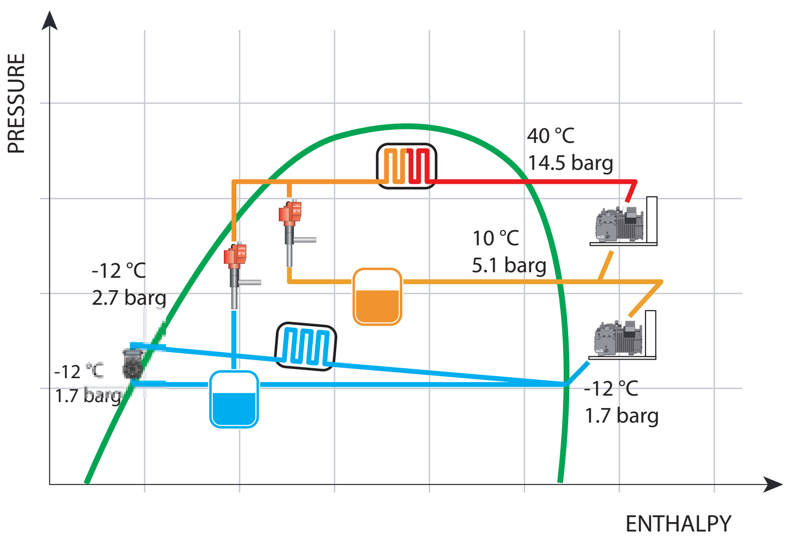


Fig. 3b - P-H diagram of a R-717 two-stage refrigeration system

4. Cascade systems

In this configuration there are two set of compressors, one in a high temperature circuit and another in a low temperature circuit. A heat exchanger between the two circuits, called the cascade condenser, acts as a condenser for the high temperature circuit and an evaporator for the low temperature circuit.

The two refrigerants can be the same or different for each circuit. One common practice is to use R-717 for the high temperature side and R-744 for the low temperature side. This means that less ammonia is used and the system is more efficient compared to a two-stage ammonia-only system.

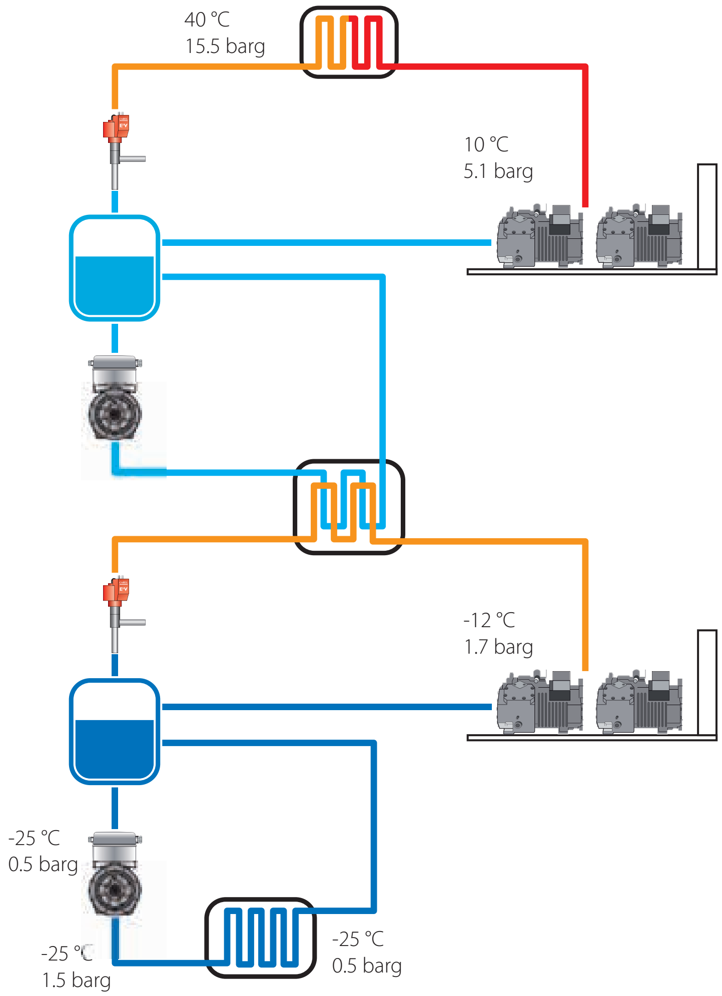


Fig. 4.a - Scheme of a R-717 cascade refrigeration system

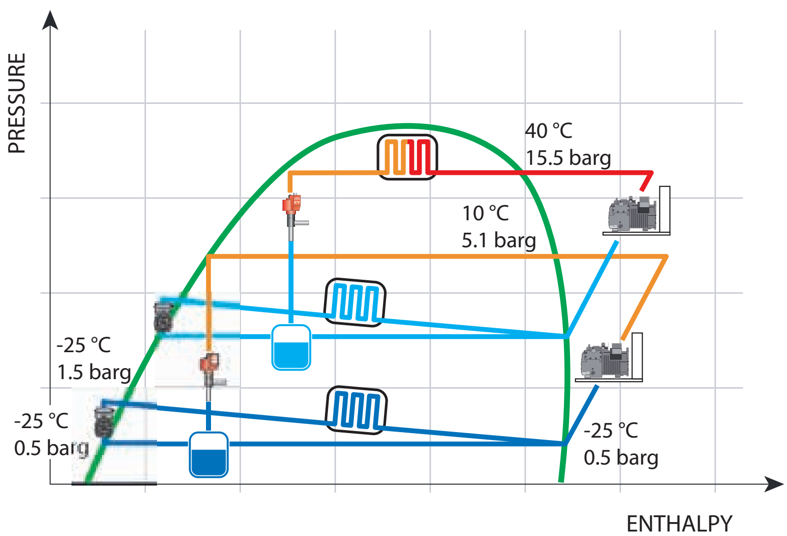


Fig. 4.b - P-H diagram of a R-717 cascade refrigeration system

5. Low-charge ammonia system[8]

Optimised system

This involves a traditional industrial ammonia refrigeration system that is further optimised with low-charge components, such as specifically-designed evaporators, controls, heat exchangers, compressors and condensers. A properly-designed low-charge optimised system uses less than 2.7 kg of ammonia (from 0.06 kg/kW to 1.3 kg/kW[9]), and therefore fewer vessels, fewer pipes, smaller pipe diameters and no pumps. Nevertheless, it still needs an equipment room.

Packaged system

A packaged ammonia system eliminates the huge quantities of ammonia inventory and piping by moving to smaller self-contained systems that are usually placed on the roof/ground outside, avoiding any dangers due to leaks. These self-contained systems have an ammonia charge of about 0.6 kg/kW and usually combine the compressor, evaporator valve system and control systems into one easily-installed and movable packaged system.

Cascade system

The main idea is to isolate the ammonia charge, which is usually between 0.5 and 0.8 kg/kW, to the equipment room, and use CO_2 as the secondary refrigerant that can be pumped into cold rooms in the building. The system may require additional equipment to pump the CO_2, along with extra compressors and other components for the CO_2 side.

[8] Shecco, World guide to low-charge ammonia (2019)
[9] https://www.star-ref.co.uk/smart-thinking/benefits-of-low-charge-ammonia-refrigeration-systems/

High efficiency and modulating technologies

The unique characteristics of natural refrigerants, such as the high working pressures of CO_2 and the flammability of propane, lead to some adaptations when designing a system. In fact, it is especially important to use efficient technology, such as modulating components, combined with advanced control and monitoring systems. Apart from enhancing safety, modulating technology contributes greatly to increasing efficiency and reducing indirect CO_2 emissions into the atmosphere, thus also facilitating compliance with energy efficiency regulations.

1. Variable-capacity compressors and drives

An inverter is a drive comprising a complex system of control hardware, power supply and software, designed to adjust the power supplied to a motor from the main power input in order to modulate operating speed. As concerns a refrigerant circuit, it can manage the performance of compressors, pumps or fans. This means that these components can operate at variable capacity, bringing significant energy savings to refrigeration and air conditioning systems.

Compressors are the most energy consuming components of refrigeration circuits, thus the use of inverters to increase their performance is being rapidly extended. In practice, inverters provide the best way to avoid inefficient on/off cycles that reduce the compressor's seasonal efficiency. This means that, at part load or in low load conditions, an inverter-driven compressor adapts cooling capacity to system requirements without stopping it completely.

In the following graph, the green area represents the increase in efficiency at part load when using DC inverters with respect to a fixed-speed compressor. The percentages shown in that area refer to the speed range of the compressor with DC inverter: the wider the speed range, the higher the energy savings.

As can be seen, ON-OFF cycling is much less efficient up to 75-80% of load, as the refrigeration circuit takes time to reach nominal efficiency. Considering that an HVAC/R application works most of the time at part load (approximately 30% of the time at 25% of nominal load, 40% of the time at 50% and 26% of the time at 75%), energy savings when using DC inverter are quite significant.

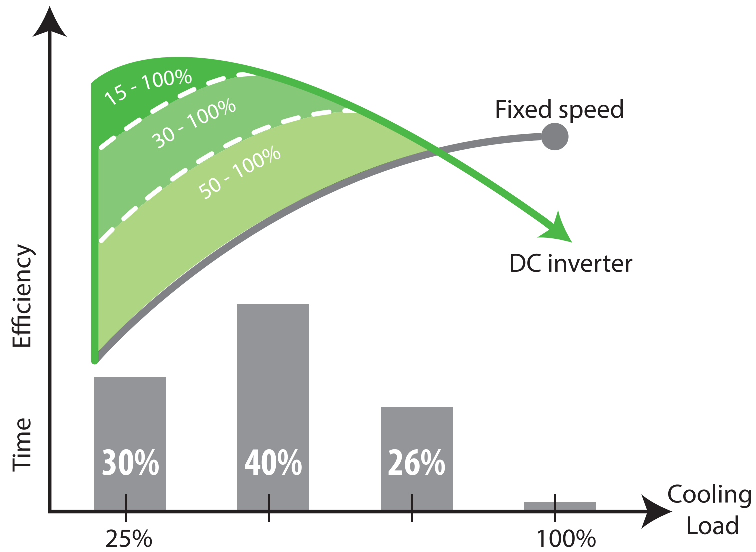
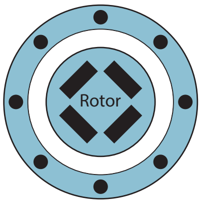


Fig. 1.a - Comparison between fixed speed and DC inverter compressors

Furthermore, when a compressor sized for nominal load is operating at lower loads, the heat exchangers are temporary oversized, bringing further benefits in terms of heat transfer. As a result of all these features, units with inverter-driven compressors have much higher efficiency in these conditions compared to rated efficiency. Indeed, it has been demonstrated that a unit fitted with an inverter-driven compressor can exceed the average efficiency of a traditional unit by up to 60%! Moreover, given that the most critical stage in the operation of a refrigerant circuit is when the compressor starts, using inverters significantly extends component life due to a lower number of starts.

Currently, the most efficient technology for inverter-driven compressors is called BLDC (BrushLess Direct Current) or simply DC. Permanent magnet brushless motors differ from more traditional asynchronous motor technology in that the compressor rotor consists of a permanent magnet instead of an electric coil. This allows higher motor efficiency (no energy is consumed to magnetise the rotor, as in the case of asynchronous motors) and a wider range of speeds, from 600 to 8000 rpm, while asynchronous motors are limited to 1500-6000 rpm. These features of DC compressors, together with the use of inverters, highlight their efficiency at part loads, giving higher seasonal efficiency and performance in terms of cooling or heating capacity control, with precise load management and constant control of the compressor envelope. It should be noted that inverter technology cannot be used without adopting electronic control systems that instantly calculate the optimum compressor speed, and electronic expansion valves, the only expansion technology that can adapt to the variations generated by the compressor.

Power+ is a CAREL inverter specifically designed for controlling compressors with BLDC technology. It can manage many types of compressors made by different manufacturers and for all kinds of refrigerants, including naturals. Rotary and scroll compressors with both vapour and liquid injection are currently driven by the CAREL Power+ drive in numerous air conditioning and refrigeration applications around the world. These include plug-in units for supermarkets, beverage coolers, chest freezers, condensing units, water chillers, rooftops and computer room air conditioners. Furthermore, the new version of Power+ has been upgraded with exclusive functions to protect the compressor and optimise the entire refrigeration system, integrating "class B" safety software that allows customers to certify the unit in accordance with international safety standards, without requiring additional components. A second exclusive CAREL proposal is a complete family of propane and CO_2 DC inverter compressors with rotary technology.



2. Electronic expansion valves

An electronic expansion valve (EEV) is a motor-driven and microprocessor-controlled expansion device designed to keep superheat at the evaporator outlet within the desired limits. The expansion device is a key component of a refrigeration circuit, together with the compressor and heat exchangers. The main advantage of EEVs with respect to traditional mechanical devices such as thermostatic expansion valves (TEVs) or capillary tubes is that they ensure significant energy savings for refrigeration and air conditioning units.

EEVs bring energy savings due to adaptive optimisation of system operating parameters. Specifically, they allow operation with a lower pressure difference, with a more significant decrease in condensing temperature and a reduction in compressor power consumption, consequently lowering operating costs.

In the following graph, the green area represents the envelope when using EEVs, showing that by decreasing the pressure difference, efficiency can be increased considerably.

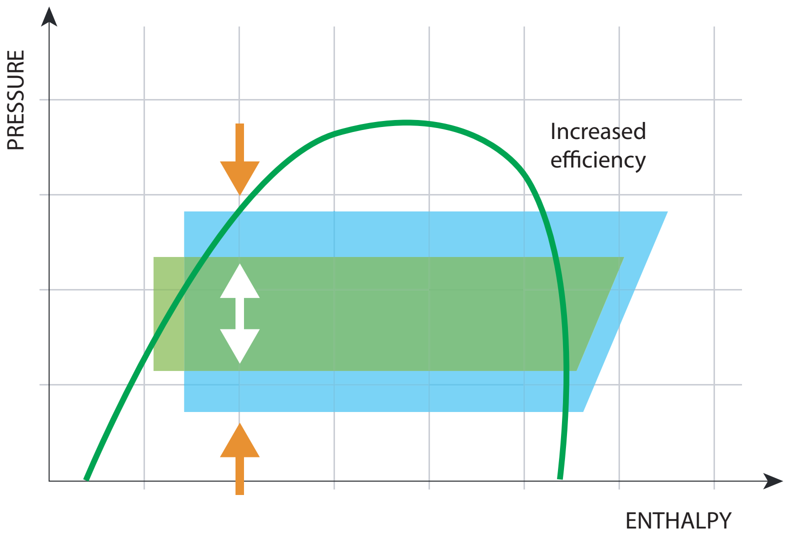


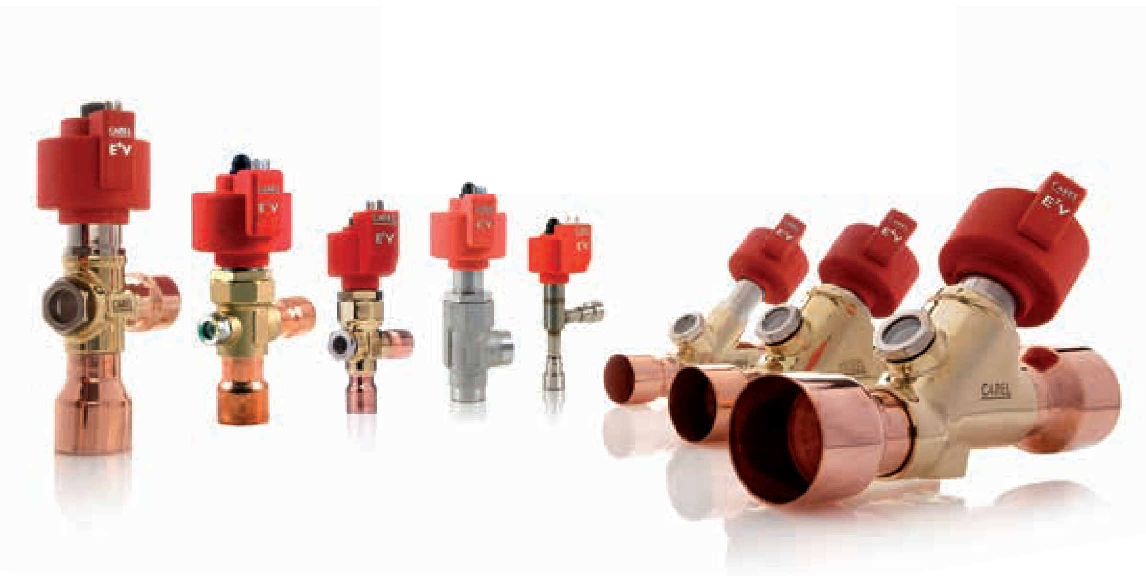
Fig. 2.a - Comparison of efficiency between a cycle with (green) or without EEV (blue).

By using EEVs combined with an optimised control system, duty temperatures (set point) are reached very quickly and are kept stable, even in the event of refrigerant leakages. The fast response time and high precision improves cooling performance, as the controller can generally keep superheat around the optimal value in every condition. Unlike mechanical devices that periodically need to be adjusted manually, EEV maintenance is easy, with no need for periodical verification of superheat control.

The range of CAREL electronic expansion valves (E^XV family) is the widest on the market. Using the same technology for the entire range ensures the key features of reliability, performance and cost optimisation. Refrigerant flow is modulated by a nozzle coupled to a torpedo-shaped opening, measuring more than 15 mm long, and covers a wide operating range. Furthermore, each size in the E^XV family can work with all types of refrigerants by simply modifying the "refrigerant type" parameter in the control system, with the exception of R-744 and R-717, which have specific models due to special requirements in terms of high pressure and corrosiveness.

Moreover, a "custom refrigerant" is always available on E^XV systems, meaning a refrigerant that has just been introduced on the market can be easily added. Compatibility with all refrigerants is a major advantage compared to mechanical devices, which need to be replaced when the system refrigerant is changed, or to other electronic expansion valves that do not include the "custom refrigerant" option.

The E^XV equal percentage profile ensures precise control in all working conditions, from part load to full capacity. Another important advantage is the fact that, by managing suction and discharge pressures, temperatures and superheat values, the E^XV is not only a superheat controller, but can also help protect the compressor. Moreover, in the closed position, the E^XV completely stops refrigerant flow, thanks to the Teflon (R) gasket on the actuator and a calibrated spring that presses this against the edge of the opening. In practice, when using E^XVs, system energy efficiency is increased by 15% to 25% annually (with peaks of up to 40%) when compared against mechanical devices.



3. Ejectors

An ejector is a device that exploits the Venturi effect and uses a primary fluid flow (typically the high pressure gas cooler outlet), accelerated through a choke, to draw in, mix and carry a secondary fluid at lower pressure to the suction side or a liquid receiver.

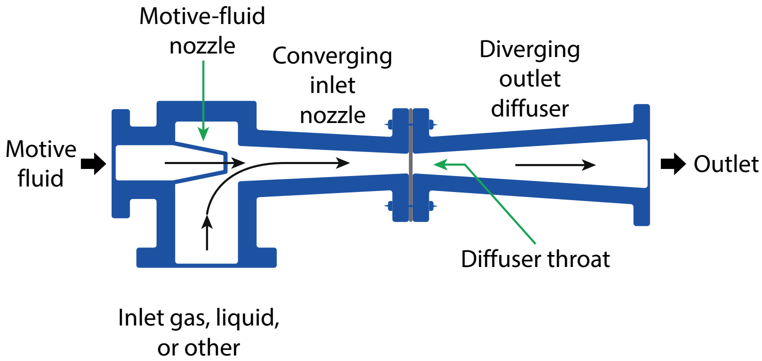


Fig. 3.a - Scheme of an ejector

The Venturi effect consists of a phenomenon in which a moving fluid inside a closed duct decreases its pressure when the velocity increases when passing through a zone of smaller section. This effect is explained by the Bernoulli Principle and the principle of mass continuity: if the flow of a fluid is constant but the cross-section decreases, the speed must necessarily increase after passing through this section. According to the theorem of conservation of mechanical energy, if the kinetic energy increases, the energy determined by the value of the pressure must decrease:

$$P_1 + \frac{1}{2}\,\rho\, V_1^2 + \rho g\, h_1 = P_2 + \frac{1}{2}\,\rho\, V_2^2 + \rho g\, h_2$$

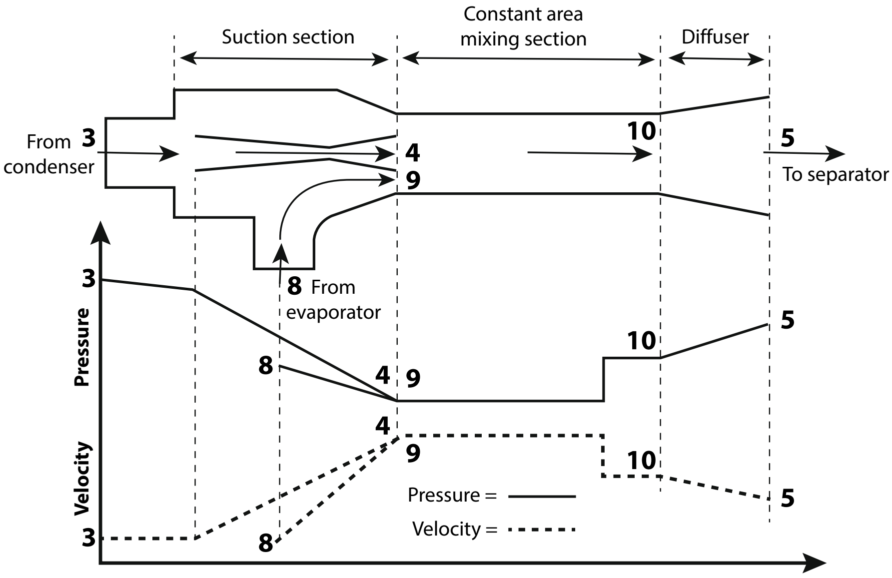


Fig. 3.b - Velocity and pressure profiles for an ejector

In refrigeration circuits, the use of ejectors reduces the compression ratio and the flow-rate handled by the compressor, guaranteeing significant energy savings in CO_2 systems for supermarkets.

Energy savings due to the use of ejectors are particularly significant for CO_2 systems operating in warmer climates, where losses due to expansion are high. However, ejectors can also be applied in cold climate locations, increasing system efficiency. Another important feature of ejectors is the fact that they extend compressor operating time by increasing the amount of vapour to be compressed.

The fundamental advantage of the CAREL Electronic Modulating Ejector (EmJ) is continuous modulation which, via dedicated control algorithms, allows the system to continuously adapt to the typical variations in operating conditions of refrigeration systems. This ensures the highest system efficiency, adapting to different system requirements in the most optimum way, especially at part load. In practice, EmJ guarantees improvements in system performance of up to 25% in design operating conditions and up to 12% overall throughout the year. The number of supermarkets using R-744 as a refrigerant is rapidly growing and ejectors are becoming an essential component, especially in warmer countries.

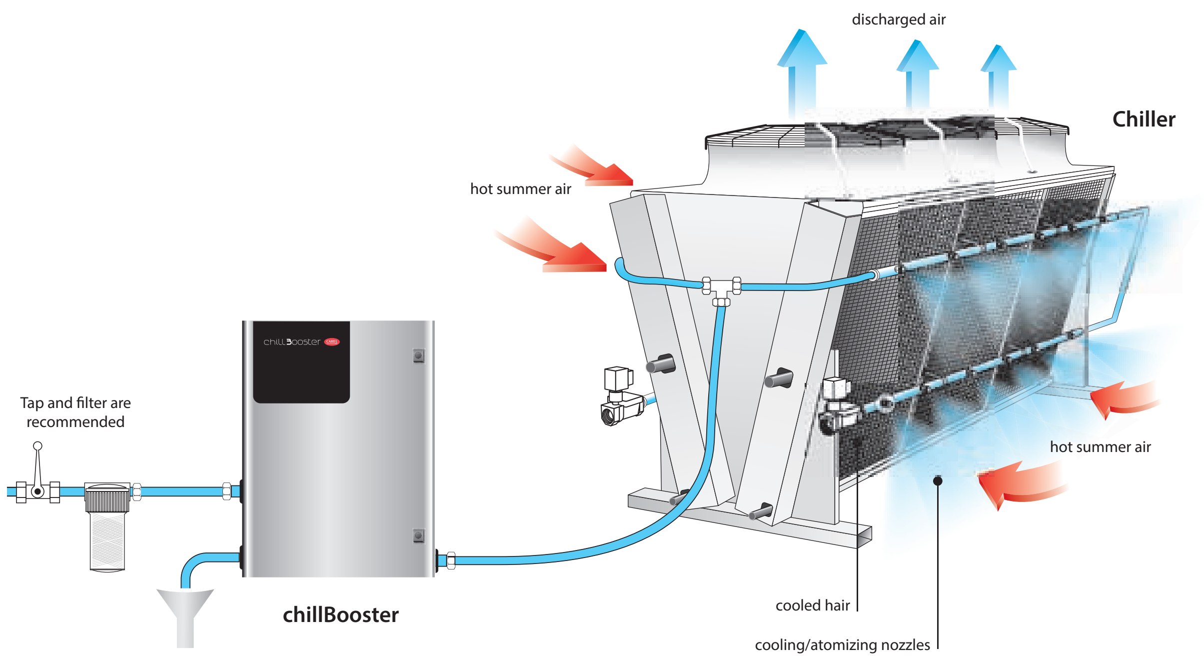
4. Evaporative cooling

CAREL offers pumping and distribution systems for indirect and direct evaporative cooling for air handling units, as well as water spraying systems for finned coil heat exchangers used, in example, as condensers for chillers, dry coolers and gas coolers. For instance, ChillBooster sprays finely atomised water into the air stream that flows through the coils. These droplets of water evaporate spontaneously, absorbing energy from the air that is consequently cooled, and comes into contact with the finned coil at a lower temperature. In this way, the heat exchanger can dissipate the rated amount of heat even when the climate is hotter than expected. Moreover, the atomised water particles do not evaporate completely before reaching the finned coil, and consequently the heat exchanger fins are wetted, further increasing overall system efficiency thanks to evaporation from the fins themselves.

Atomisers used for evaporative cooling applications can operate on untreated mains water or demineralised water, and are very simple to manage: all that is needed is a pressure switch in the refrigerant circuit. Compared to evaporative cooling systems that do not use atomised water, for example wetted media, this system has several benefits: easy installation, even in retrofit applications, more precise control with less water consumption, lower maintenance costs and no pressure drop in the ventilation system.

Overall, cooling capacity increases by at least 30%. In particular, in a typical system designed to work at an outside temperature of 26°C and a relative humidity of 50%, when using evaporative cooling at 30°C a drycooler has an equivalent capacity to operating at 25°C without evaporative cooling.

humiFog, optiMist, KEC and humiSonic are CAREL products that can be used for direct and/or indirect evaporative cooling.



High efficiency solutions with natural refrigerants: refrigeration

1. Beverage cooler with propane

The market situation has changed with respect to the past: consumers no longer just look at the initial price of the equipment, but also at the electricity costs over the life of the unit. Similarly, environmental impact is becoming more and more relevant at the time of buying an appliance. In this sense, beverage coolers have to be designed with the focus on reducing power consumption while keeping or even enhancing performance.

Moreover, the use of low GWP HFOs and natural refrigerants is being expanded due to fluorinated gas phase-down regulations all around the world. In small systems such as beverage coolers, hydrocarbons are among the most appropriate refrigerants due to their high performance. The low refrigerant charge in these applications facilitates compliance with flammability limits and explosion-proof requirements. Furthermore, the environmental image of natural refrigerants is becoming a marketing claim.

The combination of a very low GWP refrigerant in hermetically-sealed equipment (with a consequent reduction in leaks), with a variable-speed compressor and the right choice of the other components, allows important results to be achieved in terms of energy efficiency and consequently reduction in environmental CO_2 emissions. Nevertheless, there is still a possibility to improve beverage coolers: by making them smart.

IoT ("Internet of Things") can be used to improve systems based on the knowledge and analysis of historical data, which is collected by connecting different units together over the internet. Data is transformed into information, information into knowledge, and knowledge into value, and this is why it is called data intelligence. The object becomes smarter and consequently repeats the procedures that have obtained the best results. In refrigeration sector, the first steps regarding IoT and data intelligence have already been taken, and beverage coolers can benefit from these.

HEEZ is CAREL's complete award-winning[10] solution for beverage coolers with propane. By using DC inverters, EC fans, electronic expansion valves and an advanced parametric controller, this solution drastically reduces cooler power consumption compared to traditional appliances. The software includes self-adaptive logic that adjusts operation by learning from the user's habits, and can moreover identify when to work in high efficiency mode, or on the other hand when to switch to very high performance mode. Integrated wireless connectivity for interaction with mobile devices facilitates access to information for service or checks. Finally, a cloud-based monitoring system (ARMILLA) can provide reports and dashboards through complete connectivity with all beverage coolers installed on the market.

One of the main results achievable with HEEZ is the incredible increase in temperature pull-down performance. This ensures the beverages are at the desired temperature, thus boosting sales. Performance has been verified in a renowned international testing laboratory[11]. The results obtained show a 47% reduction in power consumption compared to the best-in-class solutions in accordance with the European test protocol, and a 52% reduction compared to the limits set in DOE 2017.

In summary, the latest technology can be used to build a very efficient and connected beverage cooler, aligned with market requirements and compliant with standards. HEEZ is CAREL's beverage cooler solution that responds to these challenges, using DC rotary compressors, electronic expansion valves, full variable-speed fans, self-adaptive logic and propane as the refrigerant. All of this guarantees high energy efficiency and great cooling performance while reducing environmental impact.

[10] Best environmental sustainability initiative at Drinktec 2017, https://www.foodbev.com/news/world-beverage-innovation-awards-2017-winners-revealed/
[11] http://www.re-gent.nl/

2. Condensing unit with CO_2

Convenience stores are one of the fastest growing food retail store formats, especially in emerging countries, due to the new demands of society. These stores require smaller systems with lower capacities, fewer compressors and more compact dimensions.

Condensing units are small refrigeration appliances with one or two compressors and a condenser installed on the roof or in a small equipment room. Several display cabinets and/or indoor AC units can be connected to these units, which explains their global popularity for small shops and convenience stores.

The typical cooling capacity of a condensing unit is in the range of 1 to 20 kW, containing 5 to 10 kg of refrigerant. This quantity of refrigerant excludes the possibility to use flammable refrigerants under current safety standards. This is why CO_2 is currently considered the best solution with natural refrigerants.

HECU SISTEMA is CAREL's solution for convenience stores and small shops (including cold room applications) using condensing units. The layout of R-744 circuits for one or two stages is shown in the following figure. The MT solution involves option 3 (three valves), presented in the section 2 of this document, using a transcritical compressor. For the LT solution, there are no suitable transcritical compressors, and thus a parallel compressor is used instead of the HPV valve. This involves a two-stage compression system, with a bypass that carries some of the gas directly to the receiver, thus decreasing the temperature of the refrigerant before it is compressed by the second compressor.

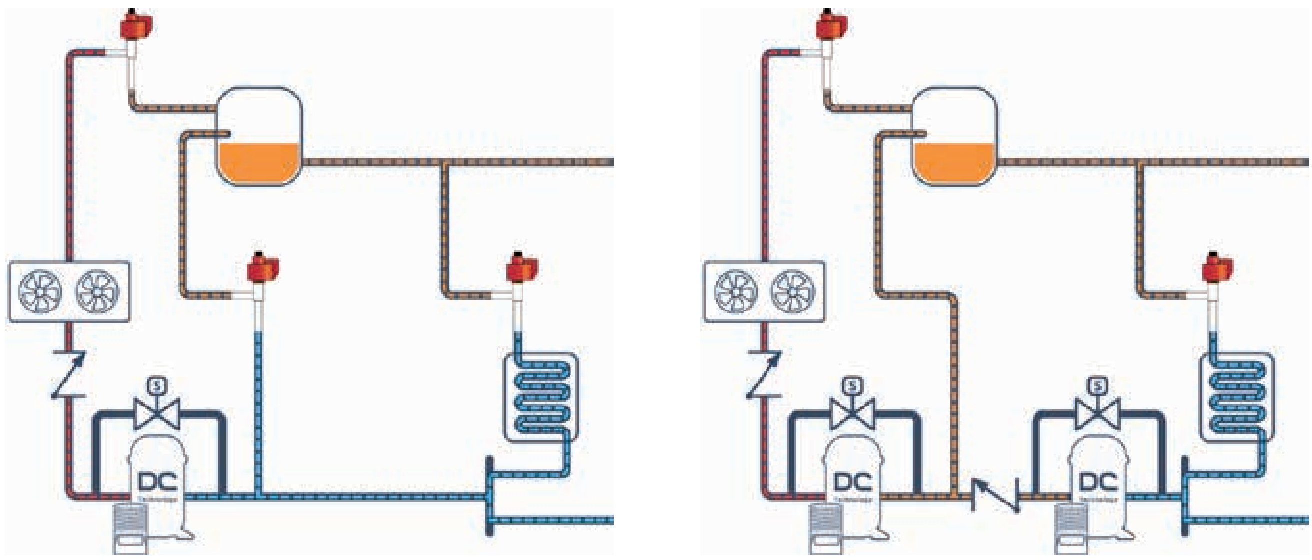


Fig. 2.a - Schemes of R-744 systems for MT and LT with HECU

HECU Sistema is compatible with HFCs, HFOs and R-744 refrigerants, and exploits the advantages of high efficiency components such as DC compressors and electronic expansion valves to provide a cost-effective and energy-efficient solution. Benefits include: a very wide range of cooling capacity modulation, low noise, low maintenance and long working life and increased food shelf life thanks to stable preservation temperature.

For small and medium systems, such as condensing units, CAREL also offers a solution suitable for R-744 booster systems: pR multi DC controller. As shown in the following figure, this solution has been designed for a three-valve configuration with both low and medium temperature evaporators. Extended modulation capacity, guaranteed by the use of a DC inverter on each compressor, ensures new levels of efficiency: up to 20% more efficient than conventional technologies. Through synchronisation with pRack pR300T, pR multi DC can manage up to 4 MT compressors and 2 BT compressors for CO_2 booster applications.

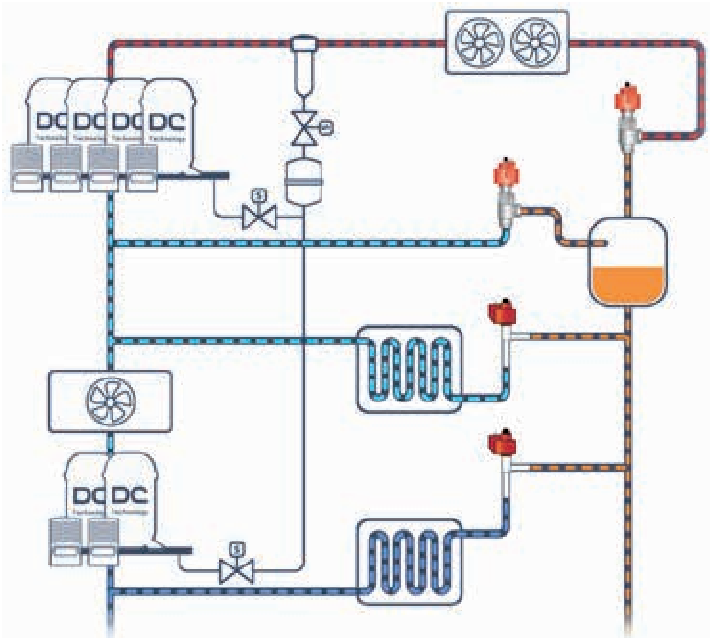


Fig. 2.b - Scheme of a R-744 system with pR multi DC controller

Product reliability is guaranteed by precise envelope management combined with an innovative oil control system. The offering is completed by full compatibility with CAREL supervisory systems, which simplify system management and further increase efficiency.

3. Plug-in and semi plug-in units with CO_2 and propane

The use of self-contained cabinets as an alternative format to compressor rack systems has expanded rapidly in recent times. A compressor rack system is no longer the best solution for many supermarkets, as it requires space to house the equipment, a huge refrigerant charge and 15% average annual refrigerant losses with up to 70% peaks due to leaks, high installation costs (including wasted materials) and poor flexibility in the store layout.

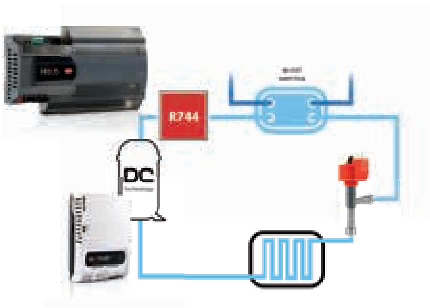
Plug & play showcases are factory assembled units with embedded refrigeration circuit used especially in medium-sized supermarkets. Depending on whether the condenser is glycol/water- or air-cooled, these showcases are called "semi plug-in" or "plug-in", respectively. The advantage of using glycol/water-cooled condensing units is that the heat of condensation is removed by the glycol/water loop, avoiding an increase in the indoor temperature in the supermarket, and the same heat can even be used for heating and domestic hot water production, bringing benefits for the unit and the entire building. On the contrary, air-cooled plug-in showcases are more flexible, due to the lack of plastic pipe connections, however they dissipate the heat into the supermarket. This means an extra cost of air conditioning in summer, while there are some savings in heating in winter.

In both cases, plug-in and semi plug-in, installation is fast as the cabinets are usually "ready to use", with only the water pipe connections needed in the field in the case of semi plug-ins. Additionally, the critical components such as the compressor are already contained in the cabinet, making it easier to install and commission. This also makes their use more flexible, as the cabinets can be moved around inside the supermarket much more easily than with other systems. A reduction in maintenance and the consequent lower costs is another key feature of both plug-in and semi plug-in units. It is also important to note that these self-contained solutions free-up the space typically occupied by the compressor racks in a traditional system, with the advantage of having a larger sales area and avoiding the noise and vibrations usually produced in the equipment rooms. Moreover, the roof of the supermarket looks better without any condensing units installed on top, an aspect that is especially important if the shop is located in an old town centre.

As regards direct CO_2 emissions, the reasons why self-contained units have a lower impact on the atmosphere than centralised systems are quite clear. On one hand, not having long copper pipes and compressor racks means a very significant reduction in refrigerant charge. On the other, the fact that there is no welding or soldering in the field and the units are factory-tested substantially reduces refrigerant leaks. R-744 and R-290 are the most commonly-used natural refrigerants in self-contained units.

The CAREL HEOS SISTEMA (another award winner[12]) is a solution for plug-in and semi plug-in units that incorporates the high-efficiency components mentioned above. The main benefits are: reduced loss of refrigerant due to a lower charge and leaks (-96%/year!), increased efficiency through the use of DC inverter compressors, improved food preservation[13], high flexibility in the shop layout, low installation costs and dramatically shorter installation times.

The first HEOS proposal for CO_2 involves single circuits for both medium and low temperature cabinets. A water chiller allows low temperature cabinets work in subcritical conditions, whereas the medium temperature cabinets work in transcritical conditions. The chiller switches on when external ambient temperature is higher than 20-25 °C, ensuring subcritical mode for low temperature cabinets.



Operation with Chiller for LT showcases

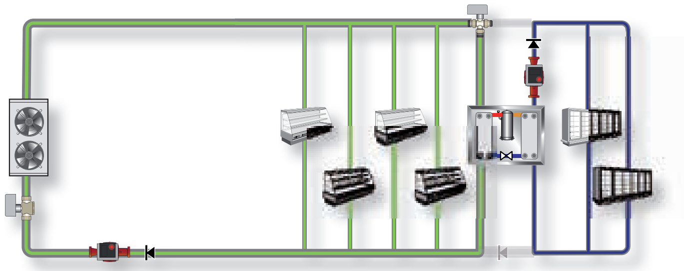
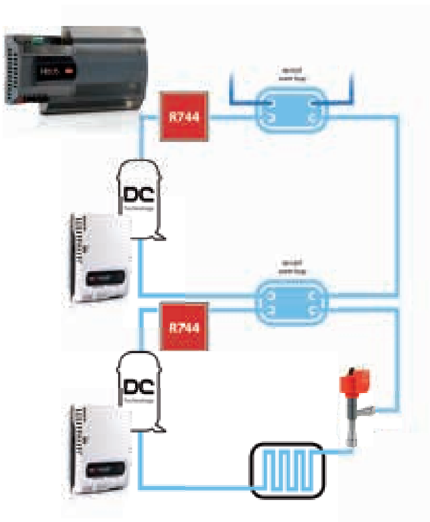


Fig. 3.a - Schemes of HEOS R-744 system with single circuits for both medium and low temperature cabinets.

The second proposal for CO_2 involves two-stage circuits in each cabinet. The high stage works at high temperature (transcritical), in order to keep the low stage working in subcritical mode.



Free cooling operation

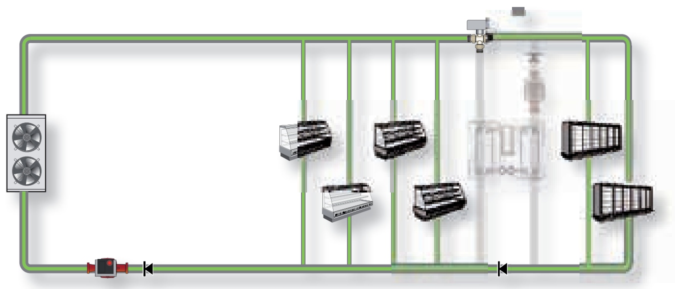


Fig. 3.b - Schemes of HEOS R-744 system with two-stage circuits in each cabinet.

These two CO_2 proposals are suitable for semi plug-in units with water loop system. There are also other possibilities, such as the use of chillers for both medium and low temperature cabinets, which can be adopted with HEOS. Detailed analysis is needed to define which is better in each case.

HEOS with propane includes two proposals. For small loads propane plug-in and semi plug-in units can be constructed using a conventional single circuit, both for medium and low temperature cabinets. Compliance of the components with IEC 60079 (standard for explosive atmospheres) facilitates the approval with respect to IEC 60335-2-89.

[12] Best refrigeration application at AHR Expo, 2016, https://ahrexpo.com/awards-winners2016/
[13] "Food preservation" white paper, https://www.carel.com/-food-preservation-white-paper

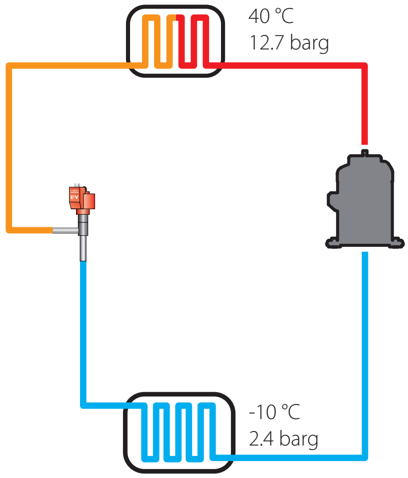


Fig. 3.c - Scheme of a R-290 system (single circuit)

For higher loads, it is possible to design a multi-circuit system with a common evaporator and condenser. The typical configuration nowadays is three circuits with 150 grams each.

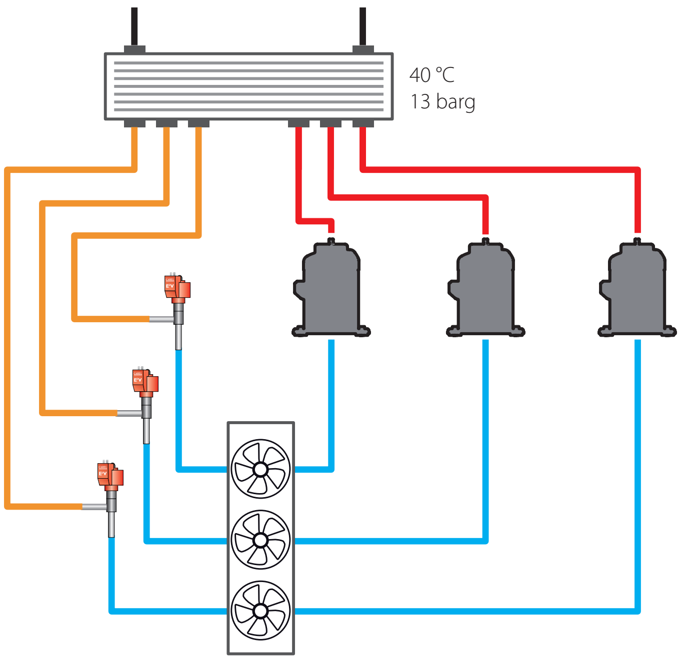


Fig. 3.d - Scheme of a R-290 system (three circuits)

With all of these options, end users can decide the advantages that best suit their needs. The use of natural refrigerants for self-contained cabinets demonstrates that high pressures, low efficiency in warm climates, flammability and restrictions in the refrigerant charge are not problems, if managed correctly.

In line with HEOS proposal, two solutions for plug-in and semi plug-in units have recently been developed: HEOSBox and HEOSone. HEOSbox is a complete condensing unit for semi plug-in cabinets based on HEOS solution. HEOSbox comes with all of the features of the HEOS solution, meaning variable-speed compressors based on DC technology and electronic expansion valves. It also includes high-value services, such as dedicated in-field and cloud monitoring and diagnostics tools for the industry: specific and intuitive dashboards in the supervisory solutions, powered by smart algorithms to enable real predictive maintenance and perfect monitoring of the tangible results in terms of energy savings and food preservation.

HEOSone is CAREL's solution for the control and management of small refrigerated plug-in units with propane, available for both medium and low temperature applications thanks to the complete line of Orione R-290 DC compressors. The synergic use of modulating devices allows freezers and coolers to maintain the highest possible energy efficiency while keeping the goods at a constant temperature.

Typical applications are chest freezers, wall standing showcase plug-in coolers for supermarkets, professional refrigerators for kitchens and food display coolers for bakeries and small shops.

4. Centralised system with CO_2

Centralised systems comprise a central compressor rack installed in an equipment room. Two main design classifications are used: direct and indirect systems.

- Direct systems are the most traditional refrigeration system used worldwide in supermarkets. These involve compressor racks in the equipment room connected to the evaporators on the display cases and the condensers on the roof via long pipes containing the refrigerant. This implies very high refrigerant charges: a supermarket with a typical rack system uses from 1,400 to 2,300 kg of refrigerant.

  A distributed system is a variation of the direct system. It is called distributed because there is no centralised compressor rack in the supermarket but rather several smaller compressor racks installed in boxes near the display cases. In these systems, the compressor suction lines are much shorter than in the conventional direct system. The compressor discharge lines are typically connected to a separate rooftop air-cooled condenser. The refrigerant circuits in a distributed system are shorter and the total refrigerant charge is about 75% of multiplex systems.

- Indirect systems: this type of supermarket refrigeration system emerged with the aim of decreasing the refrigerant charge and minimising potential refrigerant leakages. They comprise a solution with completely separate MT and LT loops: two primary and secondary refrigeration cycles with different temperature levels. Secondary fluids based on water and potassium formate, potassium acetate, glycols, alcohols and chlorides are commonly used. CO_2 is also used as a secondary refrigerant, as described in section 2 of this document.

The most popular refrigerants in these types of supermarkets, direct and indirect, have in recent years been R-404A and R-507A. Retrofit solutions include R-448A and R-449A, whereas the use of R-744 is creating an alternative technology for large supermarket refrigeration systems. Details on systems with R-744 are described in section 2 of this document, under "Carbon dioxide systems".

CAREL's R-744 solutions for compressor racks are suitable for subcritical systems (pRack 300) and transcritical systems (pRack 100T and pRack 300T).

pRack 300 (pR300) is especially recommended for subcritical cascade CO_2 systems, thanks to integration of electric expansion valves for the control of plate heat exchangers. In this way, unit performance is optimised thanks to the increased interaction between the refrigeration unit and the expansion valves.

In a cascade system, the low temperature system can communicate the cooling capacity to the driver and can also modulate the capacity of the vaporiser based on the condensing pressure of the CO_2, saving the need for additional probes and obtaining fine and accurate control of condensing pressure. Traditional superheat control is evaluated by monitoring the trend in CO_2 condensing pressure.

For small applications, pR100T is a complete and integrated solution for managing systems such as condensing units. pR100T can control: compressors (time-rotation-inverter), fans (on/off, EC), HPV valve (optimal algorithm for pressure calculation), flash valve (pressure of the receiver-safety devices connected to the HPV) and restore procedures (fault synchronisation with showcase controller).

The scalability of the pRack platform means the same user interface can be used for all of these types of applications, saving on installation costs and the use of equipment. Functions include ESS (Energy Saving Suite control system), dedicated to energy saving, which can be applied together with the monitoring system.

The pRack pR300T platform manages transcritical CO_2 systems with a view to continuous improvement, allowing users to easily manage inherently complex units. pRack 300T can be efficiently used with any supermarket system configuration, such us booster systems, parallel compressors, sub-coolers and in particular modulating ejectors.

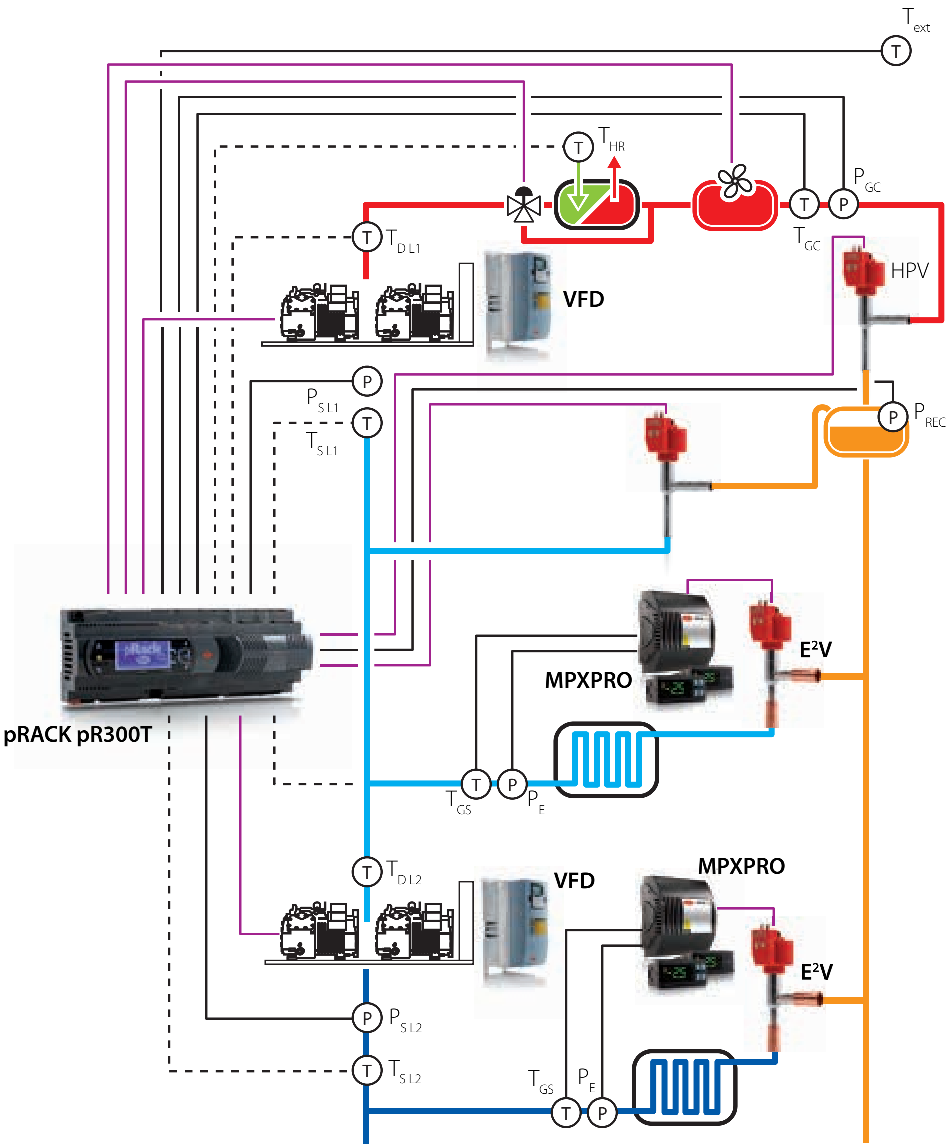


Fig. 4.a - Scheme of supercritical R-744 system with pRack pR300T

High efficiency solutions with natural refrigerants: HVAC

1. Residential heat pump

The accurate unit design and choice of components play an essential role when developing a heat pump, in order to optimise energy consumption and reduce total CO_2 emissions while ensuring safety. The need to switch to alternative refrigerants adds an extra challenge. In recent years, unit and component manufacturers have started to work together in order to develop affordable and reliable solutions, not only improving component technologies and integration in the units, but also cooperating closely from the start of the design start stage.

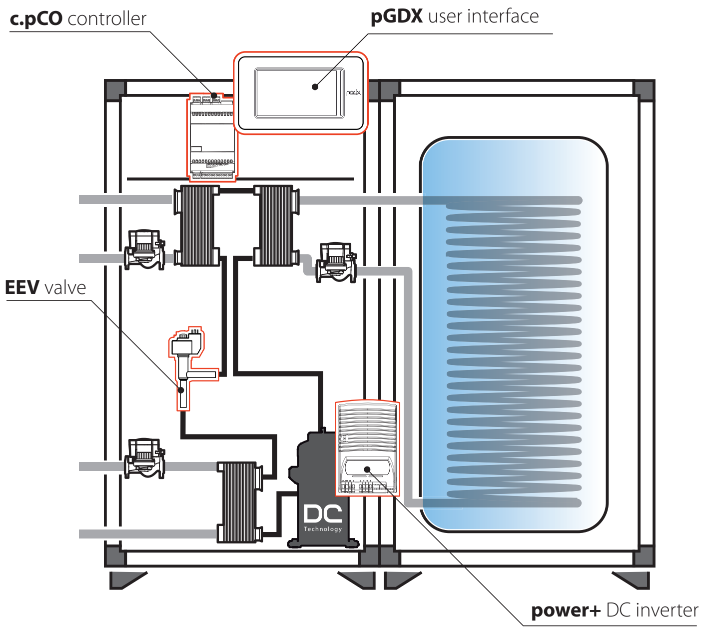
'Heat pump'[14] means an air heating product: (a) of which the outdoor side heat exchanger (evaporator) extracts heat from ambient air, ventilation exhaust air, water, or ground heat sources; (b) which has a heat generator that uses a vapour compression cycle or a sorption cycle; (c) of which the indoor side heat exchanger (condenser) releases this heat to an air-based heating system; (d) which may be equipped with a supplementary heater; (e) which may operate in reverse in which case it functions as an air conditioner.

In line with the targets established by the Paris Climate Agreement, heat pumps are a promising technology to avoid CO_2 emissions coming from fossil fuel for heat generation.

The heat pump market has significantly grown in the last years. Specifically, European heat pump sales grew by 17.7% in 2019, the fourth double-digit growth in a row![15] Reversible air/air and air/water systems contributed most to the overall gains[15].

As regards refrigerants, the lack of a retrofit alternative to the commonly used refrigerant R-410A is making the phase down of HFC refrigerants more difficult. This means that all the alternatives are valid for new systems, but cannot be used in existing R-410A systems without modifications. Among the medium and low GWP refrigerants that are suitable for new equipment, the main drawback is flammability. On the one hand, refrigerants with a GWP in the range 450-700 such as R-32, R-454B and R-452B, belonging to category A2L (non-toxic, mildly flammable), are suitable options that are being implemented on the market. R-32 is a HFC, whereas R-454B and R-452B are mixtures of HFCs and HFOs. Moreover, natural refrigerants such as propane (A3: non-toxic, flammable) and ammonia (B2L: toxic, mildly flammable) are increasingly being used. For all of these flammable refrigerants, charge limits in the range 1-1.5 kg are specified in the IEC 60335-2-40 standard, as well as other safety requirements. Finally, recent developments allow CO_2 to be used as a refrigerant for heat pumps, with specific focus on water heaters.

The increase in performance of heat pumps to help comply with Ecodesign requirements and reduce operating costs can be achieved by the use of advanced technology such as variable speed compressors, electronic expansion valves and efficient control systems. Variable-speed compressors driven by inverters provide the best way to avoid inefficient on/off cycles that reduce compressor seasonal energy efficiency. Electronic expansion valves save energy by adaptive optimisation of system parameters during operation. In particular, the system can operate with a lower pressure difference, allowing a more radical decrease in condensing temperature and reducing compressor power consumption, consequently lowering operating costs. An advanced control and supervisory system with energy saving functions is particularly important for heat pumps, which need to adapt their operation to the climatic conditions and requirements of the end user.



[14] EU Commission Regulation 2016/2281
[15] EHPA, "European Heat Pump Market and Statistics Report 2020".

c.pCO sistema is the solution CAREL offers its customers for managing HVAC/R applications and systems such as heat pumps. It comprises programmable controllers, user interfaces, communication interfaces, remote management systems and cloud services to offer the OEMs working in HVAC/R a control system that is powerful yet flexible, can be easily interfaced to the most widely-used Building Management Systems, and can also be integrated into proprietary supervisory systems. c.pCO Sistema is compatible with natural refrigerants and enables the management of refrigeration circuits using CO_2 in both subcritical and transcritical modes.

As regards parametric controllers, µChiller is the solution for complete management of heat pumps with on-off and/or DC compressors. With serial communication available across the entire family of controllers, the main unit actuators (electronic expansion valve, fan controller, compressor inverter, etc.) can be managed to optimise unit control and efficiency. The maximum configuration manages 2 compressors per circuit, with a maximum of 2 circuits. µChiller is compatible with natural refrigerants and low-GWP mixtures.

2. Chiller

Chillers are water cooling units used in commercial and industrial applications: in the former applications they are installed either stand-alone or in combination with other units, such as AHUs and rooftops, so as to obtain comfortable temperature and humidity conditions in occupied spaces; in the latter applications, instead, they guarantee stable temperature control for industrial processes.

Based on the source fluid used, chillers can be divided into two categories: air-cooled (also commonly called air/water) or water-cooled (water/water). Chillers are then further identified by the type of compressors fitted. Rotary compressors can be used for low capacities (up to 50 kW/compressor), scroll compressors for low-medium capacities (up to 80 kW/compressor), while screw and centrifugal compressors are prevalently used for higher capacities (500 kW/compressor).

The refrigerants that have mainly been used in low-medium capacity chillers during the last years have been R-410A and R-407C, whereas R-134a and R-123 have been the predominant refrigerants in larger applications. However, the phase-down of high GWP refrigerants and the accelerated increase in prices of HFCs in some countries have forced manufacturers to look for alternative solutions.

There is a wide range of refrigerants that are suitable for different sizes of chillers. For small or medium chillers, typically dominated by R-410A and R-407C, the refrigerants that can be used are the ones already mentioned for heat pumps: hydrocarbons, R-32, R-454B and R-452B. For larger capacities, refrigerants suitable for medium temperature applications, such as R-450A, R-513A, R-1234yf and R-1234ze(E) could be alternatives, as well as hydrocarbons and ammonia. R-1233zd(E) and R-1336mzz(Z) are accepted worldwide for higher capacity chillers (centrifugal), indeed their operating range makes them suitable for chillers that currently use R-123.

In this scenario, it is clear that the refrigerant trends will differ depending on chiller capacity. However, the wide range of alternatives and the fact the chillers are installed outdoors (which simplifies flammability issues) facilitate the transition to low GWP refrigerants.

CAREL offers customisable solutions for the industrial and commercial chiller market, with products that meet the main demands in this sector. For instance, industrial chillers with R-744 in transcritical mode and commercial chillers with propane are gaining ground.

High-efficiency solutions for chillers include DC technology for rotary or scroll compressors and stepped modulation for screw compressors, electronic expansion valves, an extended range of programmable controllers, and advanced applications that optimise system operation while offering ample customisation possibilities.

c.pCO Sistema and µChiller, already mentioned for heat pumps, are widely used for chillers. In particular, µChiller is able to manage air/water and water/water chillers.

3. Mobile air conditioners

European Union Directive 2006/40/EC on "Mobile Air Conditioners" or MACs introduced the ban on using fluorinated gases with a GWP higher than 150 in passenger cars and light commercial vehicles. Until then, R-134a (GWP=1430) had been one of the most widely used refrigerants globally for passenger comfort.

The introduction of a very low GWP refrigerant, R-1234yf, as a substitute to R-134a in the automotive industry introduced another critical aspect: R-1234yf is slightly flammable, thus requires further precautions for application in passenger cars and light commercial vehicles. The typical refrigerant charge in modern cars is 200-300 g, which is still manageable for an A2L classified refrigerant such as R-1234yf. This is not the case though for larger systems, such as buses and trains, where the refrigerant charge is typically above 5 kg. Managing such quantities of a flammable refrigerant is quite complicated, and requires special care in the design and installation of the air conditioning system aboard the vehicle.

The alternative to R-1234yf for mobile air conditioners is R-744, with no flammability risk but operating in transcritical mode at certain temperatures. This means that components such as the compressor and the gas cooler need to be designed for high capacities and high pressures, which entails a much heavier unit compared to those operating on R-134a or R-1234yf.

Backed by extensive experience in the use of natural refrigerants, CAREL offers products for the transport market that respond to the main challenges for the development of CO_2-based air conditioners, ready for the high pressure levels of this refrigerant in transcritical mode. The proposal includes the c.pCO platform (solution based on programmable controllers) together with electronic expansion valves and DC technology. This solution is characterised by the availability of fine temperature control in both cooling and heating modes, performance with reliable and durable products for heavy-duty operation and sustainability through algorithms for reduced energy consumption.

About CAREL

CAREL is one of the world leaders in control solutions for air-conditioning, refrigeration and heating, and systems for humidification and evaporative cooling. We design our products to bring energy savings and reduce the environmental impact of machinery and systems. Our solutions are used in commercial, industrial and residential applications. For more information visit www.carel.com.

Notes

Headquarters

CAREL INDUSTRIES HQs
Via dell'Industria, 11
35020 Brugine - Padova (Italy)
carel@carel.com

HygroMatik GmbH
Lise-Meitner-Str. 3
24558 Henstedt-Ulzburg - Germany
hy@hygromatik.de

RECUPERATOR
Via Valfurva 13
20027 Rescaldina (MI), Italy
customercare@recuperator.eu

+4000079EN - 1.0 - 01.12.2020

For more information

CAREL Asia
www.carel.hk

CAREL Australia
www.carel.com.au

CAREL Central & Southern Europe
www.carel.com

CAREL Czech & Slovakia
CAREL spol. s.r.o.
www.carel.cz

CAREL Deutschland
www.carel.de

CAREL China
www.carel-china.com

CAREL France
www.carelfrance.fr

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CAREL Ireland
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www.carelcontrols.co.za

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www.carel.com.br

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www.carel.co.th

CAREL Turkey
CFM Sogutma ve Otomasyon San. Tic. Ltd.
www.carel.com.tr

CAREL U.K.
www.careluk.com

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www.carelusa.com

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