multi PACK

Educational e-book about MultiPACK No 1

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1 Introduction

The EU F-Gas Regulation 517/2014 aims at progressively reducing the supply of hydrofluorocarbons (HFCs) to the EU market by 79% by 2030 compared to average levels in 2009-2012 (European Commission, 2014). To satisfy its requirements the average value of the Global Warming Potential (GWP) of the working fluids in use today has to be brought from the current 2000 $\mathrm{kg_{CO_{2,equ}}} \cdot \mathrm{kg^{-1}_{refrigerant}}$ down to 400 $\mathrm{kg_{CO_{2,equ}}} \cdot \mathrm{kg^{-1}_{refrigerant}}$ by 2030 in the whole refrigeration sector (Shecco, 2016). As regards supermarket applications, the commencement of the aforementioned legislative act decreed the ban of fluorinated greenhouse gases with a GWP ≥ 150 in multipack centralized refrigeration systems having a rated capacity ≥ 40 kW. An exception was made with respect to the primary working fluid circuit of cascade arrangements, in which the usage of the refrigerants with a GWP < 1500 is still allowed (European Commission, 2014). This strict imposition was due to the enormous carbon footprint featured in commercial refrigeration applications. In fact, the average annual refrigerant leakage rate related to the European food retail industry is equal to 15%-20% of the total charge, with R404A the most employed working fluid (Hafner et al., 2014a). However, on global perspectives this reaches a value of approximately 30%, with HCFC-22 the most popular refrigerant (Hafner et al., 2014a). In addition to the aforementioned regulation some European countries have approved taxes on HFC purchases, such as 55.3 €·kg^{-1} in Norway and 26 €·kg^{-1} in Spain. Therefore, transcritical CO_2 (or “CO_2 only” or pure CO_2) refrigeration systems are perceived to be permanent replacements for synthetic refrigerant-based solutions in the refrigeration sector. In fact, CO_2 (or R744) is a readily available, non-toxic, non-flammable and low-cost refrigerant possessing an irrelevant GWP and favorable thermo-physical characteristics. Also, additional energy benefits can be obtained by implementing heat recovery to partly or completely satisfy both the space heating and domestic hot water (DHW) demands (Reinholdt and Madsen, 2010; Sawalha, 2013; Polzot et al., 2016a, 2016b; Karampour and Sawalha, 2015, 2017). Furthermore, according to Reinholdt and Madsen (2010) this technique also involves satisfying payback times. The usage of such HFC-free technologies has taken root in Northern Europe thanks to their great energy and environmental performance in cold regions (Sawalha, 2008). However, due to the fact that transcritical running modes can commonly take place in such solutions, their energy efficiency is dramatically compromised in countries with a high ambient temperature. On the other hand, the coming into force of the EU F-Gas Regulation 517/2014 has led to both conspicuous advancements and a continuous cost-optimisation of “CO_2 only” refrigeration plants for supermarket applications (Shecco, 2016). Nowadays it is possible to claim that R744 has demonstrated to be the most energy efficient and environmentally benign alternative to high-GWP refrigerants in the food retail industry, since the system layout is adapted to the unique characteristics of this working fluid (Gullo et al., 2017a, 2017b, 2016b; Hafner et al., 2016, 2014a; Minetto et al., 2014a, 2014b). This has also been revealed by the enormous growth in the number of installations featuring such HFC-free technologies in Europe, more specifically an increase by three times in 2016 compared to 2013’s level (Shecco, 2016). As reported by Shecco (2016), a similar trend has been detected in both Norway and Switzerland, whereas in Mediterranean area a raise by about 8 times occurred over the same period of time. Europe is the world’s current leader in commercial pure R744 refrigeration plants, having 8732 systems out of approximately 11000 units (Shecco, 2016). In addition, the growing interest in the environment protection and the gliding temperature heat rejection in the high-pressure heat exchanger (i.e. gas cooler), as well as the various advantages (e.g. high volumetric cooling capacity, low pressure ratios) related to the design, make R744 particularly suitable as a working fluid for some heat pump units (Nekså et al., 1998). On the other hand, an enormous lack of confidence in both R744 refrigeration and R744 heat pumping solutions

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distinguishes the Mediterranean area, where the warm climate constitutes a significant challenge for such arrangements. In order to appropriately overcome this drawback, activities promoting the installation and monitoring of such HFC-free technologies in some relevant test sites in Southern Europe should be enormously fostered. A further push towards the adoption of such a refrigerant in applications involving high energy demand buildings (i.e. food retails, gyms, hotels, etc.) is being given by the continuous increase in the price of HFCs. Shecco (2016) estimated that the entry into force of the EU F-Gas Regulation 517/2014 caused that R407A, R410A, R407C and R134a went up by 10% in price in 2016, whereas R404A become 15% more expensive over the same period of time. It is also worth remarking that, thanks to its negligible GWP, HFO-1234ze(E) has also gained noteworthy attention in supermarket applications in the last few years. However, its usage has to be strongly discouraged for many reasons, such as dramatic cost, flammability, production of toxic by-products due to both its manufacturing and its decomposition into the atmosphere, etc.

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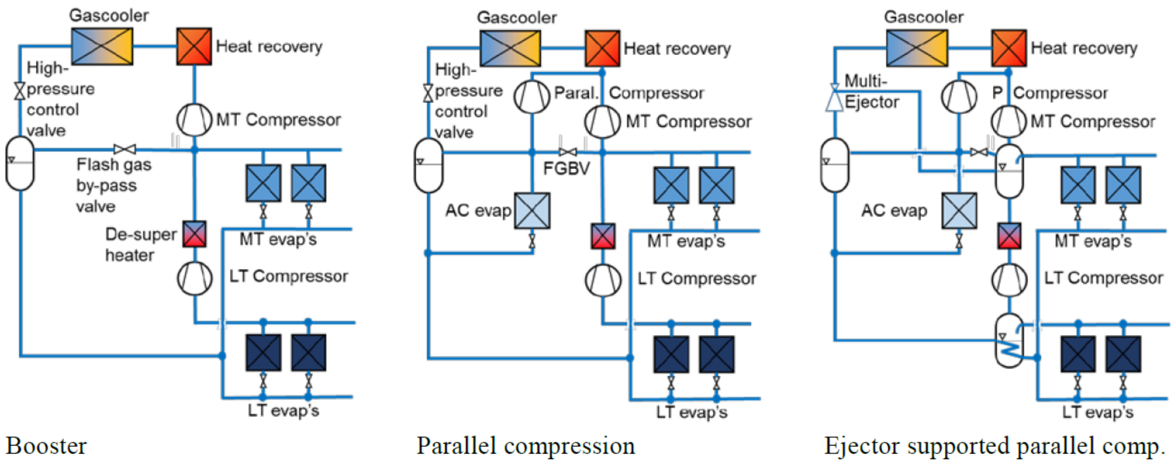
2 Supermarket applications

2.1 EVOLUTION OF CO_2 TECHNOLOGIES

The first transcritical booster system (left-hand side in Figure 2.1) was developed in 2006 by the Danish Technological Institute and installed in a small Danish store in March 2007 (European Commission, 2008). In relation to a R404A refrigerating unit, it was found that its environmental impact and required annual electricity are 4% and 52% lower, respectively (European Commission, 2008). As a result, this technology has had a great success in Northern and Central Europe, representing the 1st generation as well as the "old" benchmark for transcritical CO_2 supermarket refrigeration technologies. This solution was comprehensively studied by Ge and Tassou (2011a, 2011b).

Figure 2.1 1st (booster), 2nd (parallel compression) and 3rd (ejector supported parallel compression) generation of transcritical CO_2 refrigeration system architecture for supermarket applications (Nekså et al., 2016).



A simple expedient to enhance moderately the overall system performance is to rely on the use of a parallel (or auxiliary or AC) compressor rack (in the middle in Figure 2.1), with the intent to remove the flash gas generated in the intermediate pressure liquid receiver. This solution identifies the 2nd generation and is the current benchmark for "CO_2 only" supermarket refrigeration units. Parallel compression technology is a promising expedient for "all-in-one" (or "fully integrated") pure CO_2 systems in cold climate contexts (Karampour and Sawalha, 2017), besides representing the first step towards the use of transcritical R744 solutions in warm regions. Many studies on this solution can be found in the literature (Gullo et al., 2017b, 2017a, 2016b, 2016a; Karampour and Sawalha, 2015, 2017; Polzot et al., 2016a; Tsamos et al., 2017).

As a means to improve enormously the energy efficiency of pure CO_2 supermarket refrigeration systems, the multi-ejector concept can be adopted (Hafner et al., 2014a). The first R744 multi-ejector enhanced parallel compression installation (right-hand side in Figure 2.1) has been properly operating in a Swiss supermarket for many years (Hafner et al., 2014b). Such a technology was thoroughly investigated by many authors (Banasiak et al., 2015b, 2014; Fredslund et al., 2016; Gullo et al., 2017b, 2017a; Hafner et al., 2016, 2015, 2014b, 2014a; Hafner and Banasiak, 2016; Hafner, 2017; Haida et al., 2016a; Minetto et al., 2015a; Schönenberger, 2016). The results obtained suggest that a transcritical R744 parallel system

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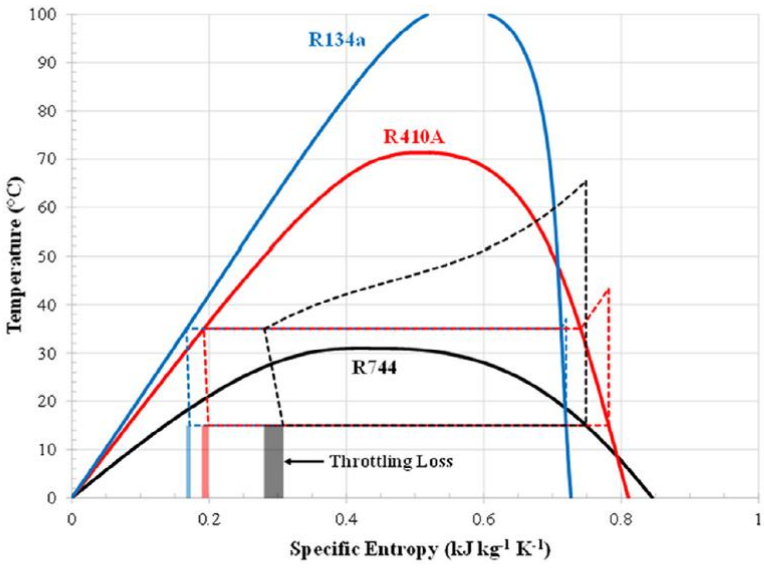
supported by ejectors is the most efficient and eco-friendly option for the European commercial refrigeration sector.

Gullo et al. (2017b) showed that, compared to a conventional booster unit, the adoption of parallel compression can lead in theory to energy savings by 3.6% and 5.7% in Milan and Athens, respectively. In the same locations, the energy conservation achieved values of about 25% over the previously mentioned baseline. Also, the authors highlighted that approximately 22% of the energy could be spared with the aid of the multi-ejector concept in relation to parallel compression technology.

2.2 THE MULTI-EJECTOR CONCEPT

Any throttling valve operates (roughly) isenthalpically causing a drop in the refrigerating effect due to the conversion of the refrigerant kinetic energy generated by the pressure drop into friction. In order to recover part of this energy content, a two-phase ejector can be employed. Such a device features cheapness, the absence of moving parts, and theability to handle two-phase flows with no damage. Bilir and Ersoy (2009) asserted that this solution is particularly promising for refrigerating applications operating in tropical countries and desert area. However, the enhancements in Coefficient of Performance (COP) achievable by adopting an ejector for work expansion recovery are strongly related to the select working fluid. On the one hand, in fact, the exergy destruction rates of the expansion valve belonging to the refrigeration unit using synthetic refrigerants (e.g. R134a and R410A) are usually low (Figure 2.2). On the other hand, these become enormous when it comes to R744 refrigerating systems. This is due to the occurrence of transcritical running modes, which entail massive differences between the rejection and absorption pressure (Figure 2.2). As a consequence, greater opportunities in terms of energy efficiency improvement are offered, as the recoverable expansion work is much higher than for conventional working fluids, especially with rise in hot sink temperature. According to Lawrence and Elbel (2015), in fact, the CO_2 ejector efficiency (defined in accordance with the one proposed by Elbel and Hrnjak, 2008) ranges from 0.2 to 0.3, whereas the high-GWP ejector efficiency is usually below 0.2. This means that 20%-30% of the expansion work, which is generally dissipated, is used to increase significantly the compressor suction pressure.

Figure 2.2 Throttling losses related to a vapour-compression refrigeration system using R744, R134a and R410A in a T-s diagram (Elbel and Lawrence, 2016).



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It is important to highlight that a single constant-geometry ejector is not able to control precisely the discharge pressure, which plays a crucial role when it comes to attaining a relevant energy efficiency for transcritical CO_2 systems (Ge and Tassou, 2011b). Either an adjustable needle-based ejector or the multi-ejector concept can be adopted to achieve such objective more appropriately. The former implies that an unsatisfactory ejector efficiency is obtained over a broad operation range. In order to take steps towards this gap, Hafner et al. (2014a) introduced the multi-ejector concept. According to Banasiak et al. (2015b), in fact, a multi-ejector module is able to control the heat rejection pressure and, simultaneously, to recover expansion work more suitably than an individual fixed-geometry ejector. This technology relies on various devices of different sizes and connected in parallel. Therefore, the number of employed ejectors is constantly varied so as to match the required capacity in any operation condition. In particular, a multi-ejector block consists of usually 4-6 vapour ejectors and generally 2 liquid ejectors. The vapour ejectors are used to pre-compress a large amount of the refrigerant, implying that the suction pressure of parallel compressors is substantially higher than that of medium temperature (MT) compressors. As a consequence, the higher the outdoor temperature, the more unloaded the MT compressors and thus the more significant the energy savings obtained. On the other hand, the liquid ejectors are devoted to recirculate some liquid back to the evaporators to eliminate the dry-out phenomenon and increase their corresponding operating temperature. Haida et al. (2016b) investigated two liquid ejectors of different size belonging to a multi-ejector module. Girotto (2017) claimed that a liquid ejector featuring an efficiency of 8% permits improving the global yearly performance by 15%, whereas a vapour ejector with a peak efficiency of 30% increases the overall annual performance by 5%. This is due to the significant $\Delta p/\Delta t$ ratio and the extremely favourable heat transfer performance of R744, which imply that the superheating is particularly detrimental to transcritical CO_2 refrigeration solutions. As a consequence, the possible replacement of the conventional dry-expansion evaporators with overfed heat exchangers would lead to substantial energy savings on the part of such systems. It was found that overfed evaporators have an operating temperature 6 K and 8 K higher than MT and LT dry-expansion evaporators respectively (Hafner et al., 2014b; Hafner and Banasiak, 2016; Schönenberger, 2016). As additional energy benefits, this allows to reduce the frost formation and number of defrost cycles with respect to a conventional system (Hafner et al., 2014b; Hafner and Banasiak, 2016; Schönenberger, 2016). Furthermore, Minetto et al. (2014a) estimated that the use of liquid ejectors would yield a decrease in the compressor energy consumption by approximately 13% with respect to a conventional configuration (the assessment was based on an outdoor temperature of roughly 16 °C and an air temperature of about 0 °C). Compared to a R404A-unit, Gullo et al. (2016b) assessed a reduction in annual energy consumption ranging from 8.2% (in Seville) to 12.3% (in Rome) by using MT overfed evaporators and parallel compression.

The reliability and the manufacturability of a multi-ejector module have already been verified, and its control system has already been efficaciously put in practice (Banasiak et al., 2015b; Banasiak et al., 2014; Hafner et al., 2016; Hafner et al., 2014b; Schönenberger, 2016). Banasiak et al. (2015b) implemented the design, the manufacturing and the performance mapping of a multi-ejector rack for commercial refrigeration purposes. Hafner et al. (2014b) suggested that such a solution leads to an energy saving of 12% over the technology based on parallel compression in a Swiss store. The multi-ejector concept permits increasing the system efficiency up to 30% in relation to a conventional booster unit, particularly at high external temperatures (Hafner et al., 2014a). A multi-ejector based configuration operating in a food retail located in Bari (Italy) consumes 22.5% less electricity than a conventional one-stage CO_2 refrigerating unit (Minetto et al., 2014b). Haida et al. (2016a) experimentally revealed that a multi-ejector R744 refrigerating system enhances the COP by 7% compared to a R744 unit employing parallel compression. With the aid of multi-ejector concept, energy savings between 15% and 25% in relation to a R744 refrigeration unit with parallel compression in two Swiss supermarkets were estimated by

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Schönenberger (2016). The author pointed out that the results are strongly depending on the heat need, the application and the weather conditions. The field measurements collected by Fredslund et al. (2016) from various supermarkets brought to light that, similarly to what has been evaluated in the laboratory, vapour ejector efficiencies above 0.25 are achievable. Also, drops in the energy consumption ranging from 10% to 15% at the external temperature of approximately 30 °C were assessed for a solution with and without coupling with the AC unit, respectively. Gullo et al. (2017a) showed that, theoretically, a "CO_2 only" system equipped with a multi-rack block in a supermarket of average size located in Mediterranean Europe leads to energy savings of 20-25% compared to a R404A direct expansion unit. The theoretical assessment by Gullo et al. (2017b) highlighted that the multi-ejector concept permits achieving a fall in the energy consumption by 31.8%÷37.1% in a cold climate context (i.e. Oslo), 17.9%÷33.6% in mild climates (i.e. Frankfurt, Milan) and 19.9%÷24.6% in warm places (i.e. Athens) compared to an R404A unit. With respect to real applications, a hypermarket using this technology was open in Timisoara (Romania) in 2015. The usage of a multi-ejector arrangement combined with the heat recovery implementation and the DHW production are supposed to lead to a reduction in the energy consumption of up to 13% in relation to a solution with parallel compression (Frigo-Consulting LTD, 2015). According to Girotto (2017), today approximately 50 supermarkets relying on the multi-ejector concept have been installed.

The multi-ejector block and its main components are showed in Figure 2.3. Up to 6 ejectors (2), activated by a conventional coil (3), are hosted within the multi-ejector block (1). The gas cooler/condenser is connected to port 4, whereas the suction of the refrigerants occurs through port 5. Port 6 is used for discharging the total amount of refrigerant, while the sensors (7) for each port measure the pressure. Besides the aforementioned energy advantages, Girotto (2017) highlighted that many others can be related to the usage of multi-ejector concept, such as reduction in the discharge temperature, a simplified control of evaporators, etc.

It is worth highlighting that some energy benefits can also be attained by employing an expander as a substitute for the conventional expansion valve. However, this presents the same complexity and high cost of compressors, besides being easily damageable owing to the presence of a large amount of liquid.

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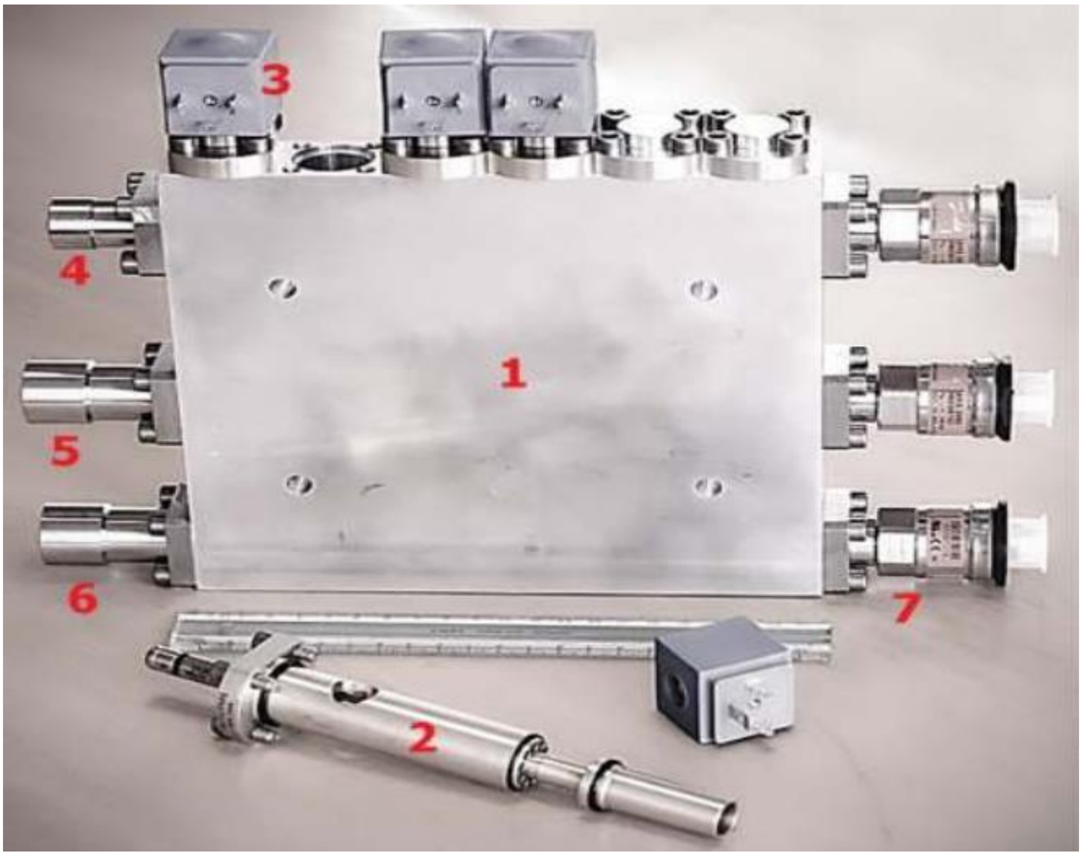
Figure 2.3 Multi-ejector block and its main components (Hafner and Banasiak, 2016).



2.3 "ALL-IN-ONE" CONCEPT

The refrigeration unit is responsible for the largest share of electricity (i.e. roughly 33%) in a supermarket (Cecchinato et al., 2010). Other additional significant consumptions, i.e. about 20% of the total electricity consumption, are owing to heating and air-conditioning demands (Cecchinato et al., 2010; Hafner et al., 2014a). As suggested by Hafner et al. (2015), an expedient to reduce the cost related to all these needs is the so-called "all-in-one" (or "fully integrated") concept. This is expected to reduce enormously the total investment, maintenance and running costs associated with transcritical CO_2 refrigeration systems for supermarket applications, especially the ones located in warm places. Karampour and Sawalha (2015) defined the technologies applying this concept as standard in the current food retail industry. "All-in-one" units are capable of providing the whole air-conditioning (AC), refrigeration and DHW reclaims, besides meeting most of or even the entire heating need of the selected supermarket.

The solution sketched in Figure 2.4 represents an "all-in-one" transcritical R744 refrigerating solution for food retails located in Mediterranean Europe. The multi-ejector concept permits overfeeding the MT overfed evaporators, whose operating pressure is around 33 bar (i.e. t_{MT} = -2 °C) rather than about 28 bar (i.e. t_{MT} = -8 °C) as for dry-expansion heat exchangers. The low evaporating pressure related to low temperature (LT) display cabinets and LT cold storage rooms, which also operate with no superheating (i.e. overfed evaporators), is kept at about 17 bar with the aid of the LT compressors. The liquid coming out of these evaporators is then collected in the accumulator located upstream of the LT compressors. The working fluid exiting the LT compressors is generally de-superheated before being drawn by the parallel compressors. Also, the operation time of the AC compressors can be extended by linking the LT

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to them. The resulting increase in the annual operating time of the auxiliary compressors allows to increase the energy advantages related to their use and to decrease the maintenance issues, as pointed out by Minetto et al. (2014b). To avoid high installation cost and improve the compactness of the refrigeration packs with various annual cooling demands of various suction groups, the compressor suction towards the different suction groups needs to be modified according to the operation conditions. Depending on the status of the on/off valve upstream of the compressors, these are either connected to the MT- or AC-suction. This leads to a “gap-free” control of the cooling capacity over a wide running range. As regards the solution sketched in Figure 2.4, only one compressor is connected directly to the AC and MT suction group. The heat recovery and rejection part consist of two different sections. The gas cooler on the right-hand side in Figure 2.4, which is used in summertime, can be by-passed in order to provide the required amount of DHW and/or space heating. The section on the left-hand side in Figure 2.4 is employed in more extreme operation conditions (i.e. coldest and hottest days of the year). This features an exterior heat exchanger (HX) as an additional heat source in heating mode to provide the whole heating demand even in case of limited internal loads. The whole amount of the refrigerant coming out of this heat exchanger is then drawn by the AC multi-ejector module. On the other hand, the exterior heat exchanger performs as a gas cooler for the parallel compressors in AC mode. As shown in Figure 2.4, the water of the fire water tank can be used as an auxiliary heat sink to further reduce the temperature of CO_2 in the high-pressure side at high outdoor temperatures. The temperature of such a tank can be dropped with the aid of a dry cooler at night. Also, the simultaneous usage of the ice-water cooling evaporators (at the bottom left-hand side in Figure 2.4) and that of the AC multi-ejector rack permits the parallel compressors to have a high suction pressure. The first evaporator interacts with a separator tank at 42 bar (i.e. about +7 °C). The refrigerant, which is provided by gravity, allows to cool down the working fluid at 12 °C returning from the building. On the other hand, the second evaporator allows to bring the temperature of the working fluid further down to 7 °C as more cooling capacity is necessary. Thus, the AC multi-ejector block draws the vapour from the second evaporator and the entire amount of the refrigerant is discharged into the separator related to the AC compressors.

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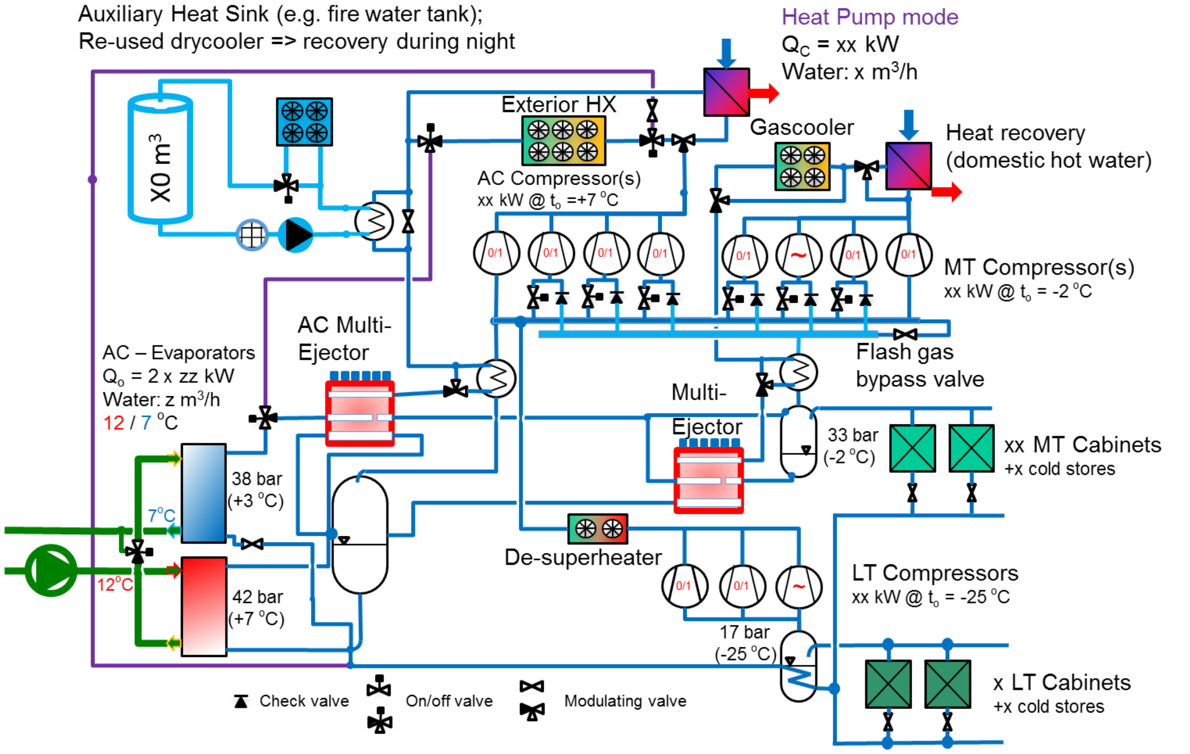
Figure 2.4 Fully integrated CO_2 refrigeration system for supermarkets located in Southern European locations with LT and MT cooling loads, hot water demand, heating & cooling demand for the building and an auxiliary heat sink (Hafner, 2017).



Also, it is worth remarking that the solution equipped with the multi-ejector rack guarantees a significant level of safety. In fact, in case of failure of the auxiliary compressors, the flash gas can be removed from the intermediate pressure liquid receiver by employing a vapour by-pass valve. In addition, in the event of the possible malfunction of the liquid ejectors or a reduced amount of liquid, the evaporators can be switched to the superheated mode in any operating conditions. Furthermore, the system is also equipped with conventional expansion valves downstream of the gas cooler in order to, if it is necessary, substitute (or simply work in parallel with) the vapour ejectors. Moreover, the auxiliary compressors can always take over the MT compressors. Finally, the presence of the separator at medium pressure and that of both a low pressure receiver downstream of the LT evaporators and the internal heat exchanger prevent the corresponding compressors from drawing any liquid.

The usage of water as the energy carrier implies that many heat exchangers need to be adopted with a consequent deterioration in the overall efficiency of AC and heating units. The problems related to water corrosiveness can be avoided by adopting suitable precautionary measures (i.e. water/inhibitor mixture), which lead to overall performance worsening. Also, a large amount of the total investment cost is owing to the water circuit. These drawbacks can be overcome by using R744 for direct cooling and heating fan coils installed inside the store, as the represented in Figure 2.5. A similar approach can also be adopted for the air curtains. As a consequence, no space for water tanks and pumps is necessary and the total cost of the heating and cooling equipment can be decreased. Also, heating, ventilation and air-conditioning (HVAC) units can be more quickly installed. On the other hand, close attention has to be paid to both the high operating pressures present inside the public part of the building and the applied heat exchanger coil design (i.e. design for dual operation).

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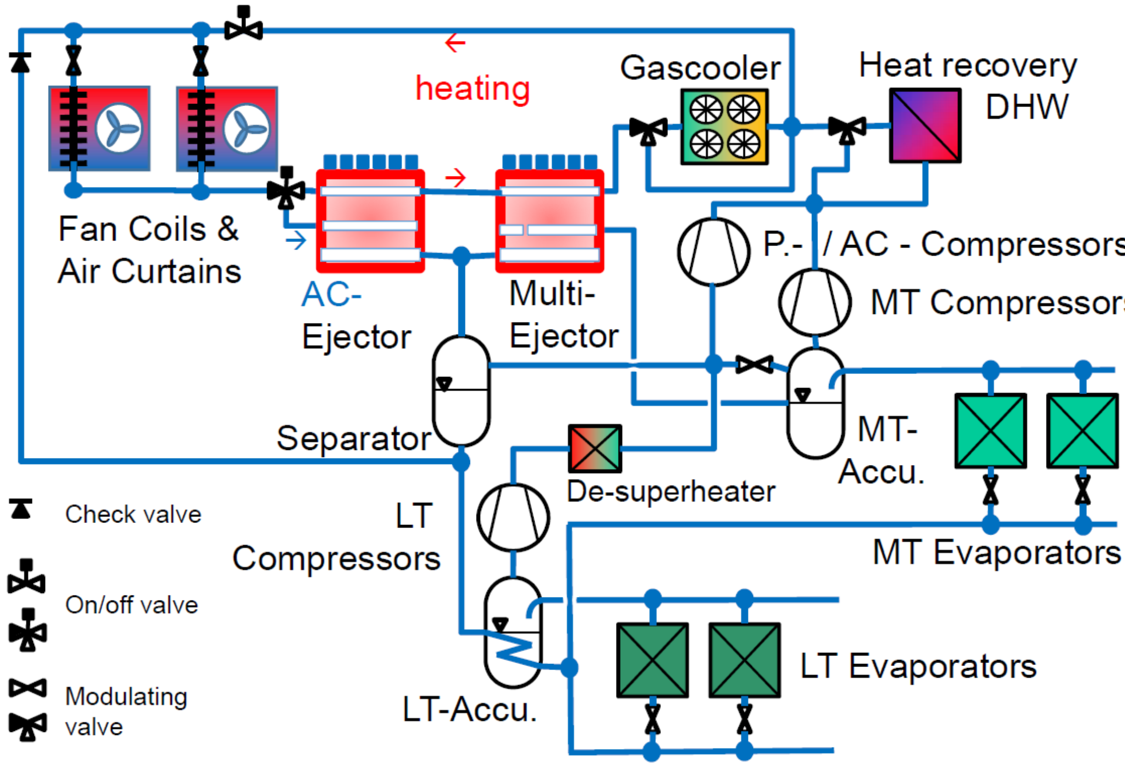
Figure 2.5 Integration of direct heating and cooling fan coils and air curtains in CO_2 commercial refrigeration units equipped with AC multi-ejector module.



In Figure 2.6 and 2.7 two different solutions with no multi-ejector block dedicated to AC units are represented. In AC mode the expansion valves upstream of the fan coils and air curtains are employed for suitably feeding these units operating as evaporators, as sketched in Figure 2.6. On the other hand, in heating mode fan coils and air curtains are used for directly rejecting some heat into the building and the gas cooler is by-passed. In the more advanced layout shown in Figure 2.7 the multi-ejector rack recovers some expansion work also as AC mode occurs.

As the "all-in-one" and multi-ejector concepts are relatively new, few field measurements are still available in the open literature. Hafner et al. (2016) collected some data from a refrigeration system operating in a food retail located in Spiazzo (Northern Italy) at outdoor temperatures between 22 °C and 35 °C. The energy consumption was found to fall from 15% to 30% compared to the configuration with parallel compressor, besides providing the whole AC demand of the store. The outcomes strongly depended on both the AC need and the external temperature. In case of integration with the AC unit, a R744 ejector supported parallel system consumes from 16.6% to 26.2% less electricity than a separated HFC arrangement depending on the size of both the AC system and the supermarket, as well as on the selected locations, as theoretically shown by Gullo et al. (2017a). As for real applications, Italy's largest hypermarket (10000 m^2) started recently operating in Milan employing an "all-in-one" CO_2 configuration with multi-ejector arrangement (Danfoss, 2016). Thanks to this technology as well as an integrated control of HVAC, light and refrigeration, the energy savings are expected to be around 50%.

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Figure 2.6 Integration of direct heating and cooling fan coils and air curtains in CO_2 commercial refrigeration units (ejector partly by-passed during AC) (Hafner, 2017).

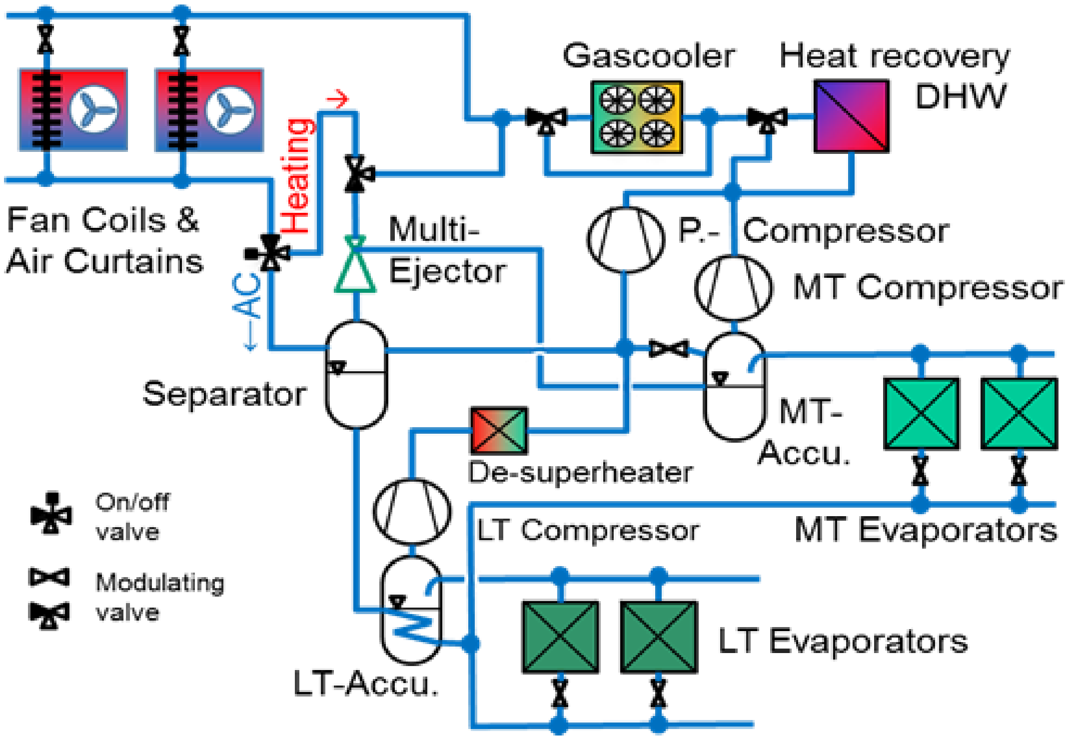
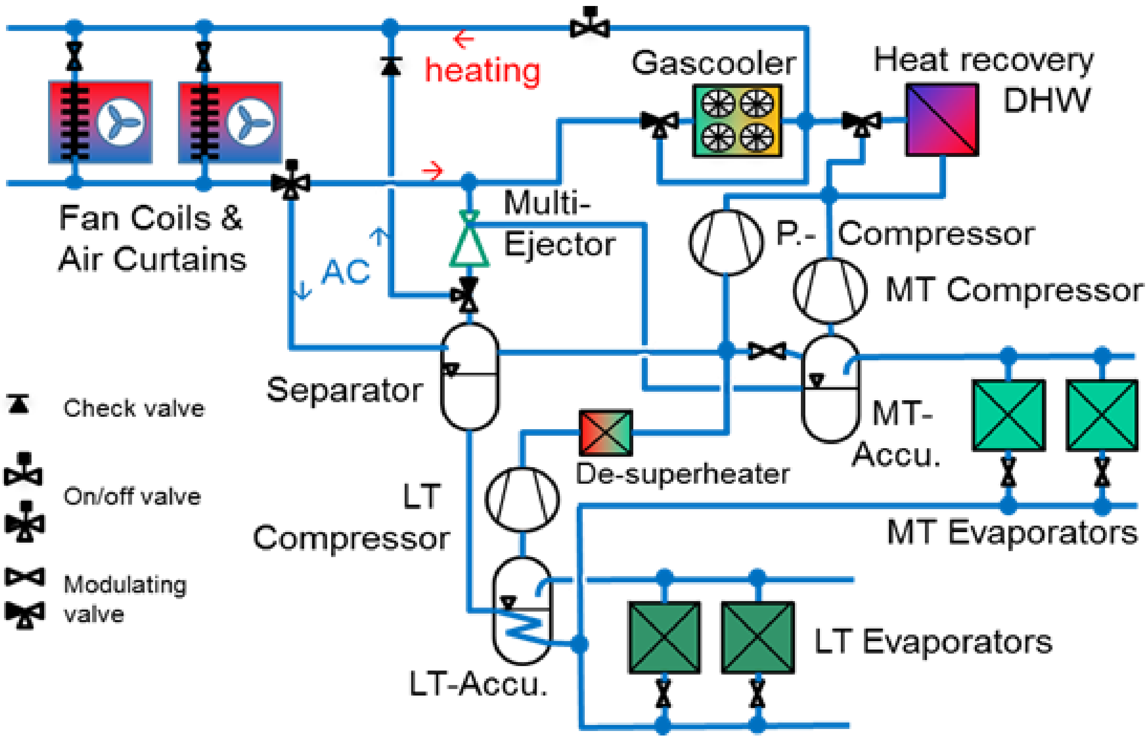


Figure 2.7 Integration of direct heating and cooling fan coils and air curtains in CO_2 commercial refrigeration units (ejector utilized also during AC) (Hafner, 2017).



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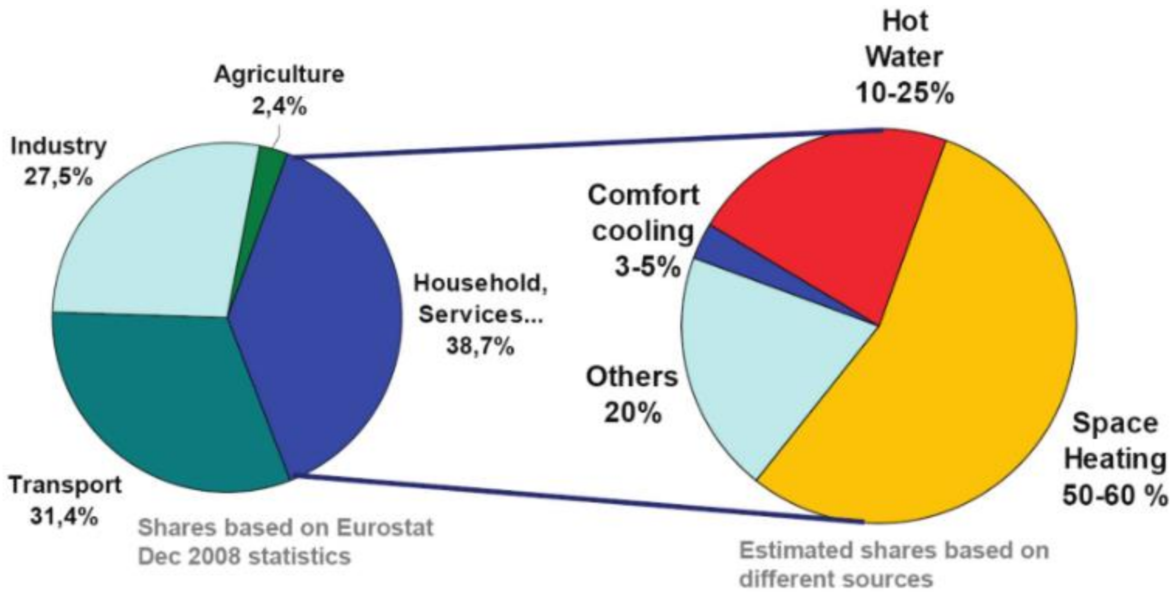
3 Reversible heat pumping applications

The great improvement of the living standards in the developed countries and the rapid growth in the last few years of some developing ones have considerably promoted the spread of reversible heat pump systems. By means of such solutions, in fact, different human needs can be satisfied, such as food preservation, thermal comfort, domestic hot water production, etc. (Hafner, 2015).

Figure 3.1 depicts the final energy consumption by sector, highlighting that in the EU the households, services, etc., feature higher total energy consumption than industrial and transport sectors due to the large requirements for space heating and hot water production. Also, Jakobs et al. (2010) claimed that food and chemical processes are the main users of energy in Italy, which implies that large amounts of water up to 100 °C are required.

Figure 3.1 Final energy consumption by sector in European Union (Jakobs et al., 2010).



Also, some sectors, such as multi-family residential and office buildings, food preservation sector, dairies, etc., have noteworthy concurrent needs of warm water, hot water and cooling. In food processing, working fluids in the range 25 °C÷95 °C for heating reclaims and 0 °C÷15 °C for cooling needs are simultaneously required, causing large electricity consumptions. In these applications, a R744 heat pump can efficiently operate as a stand-alone system to cover the DHW needs (for hotels, gyms, hospitals, etc.) in combination with separate solutions for space heating and cooling demands or as an integrated unit. The latter is a more cost-effective option thanks to its lower investment and installation costs related to its compact design. It is worth remarking that the sector of both air-conditioning and heating unit for residential and commercial buildings is still widely dominated by HFC-based reversible heat pumps, leading to massive contributions to climate change. The number of CO_2 heat pumping technologies for hot water production almost doubled from 2010 to 2011 in Europe. This was due to two main causes:

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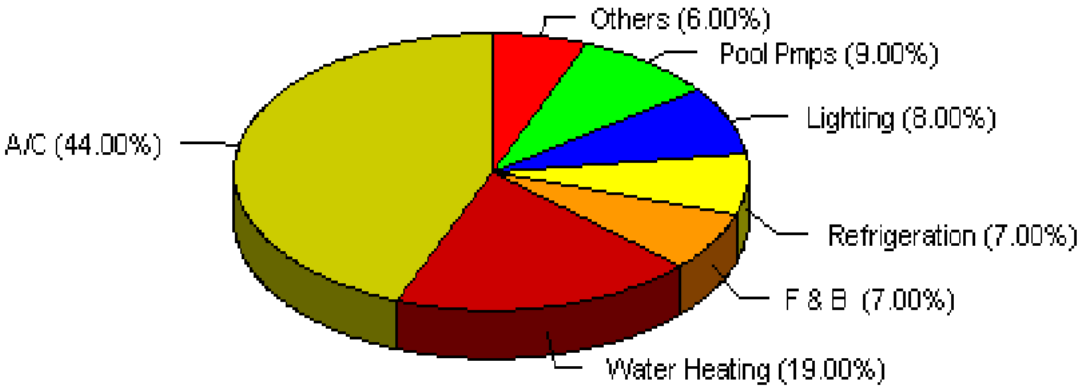
- the ever-stricter European building codes and regulations, whose adoption caused a great reduction in heating demand and a noteworthy interest in sanitary hot water needs. Furthermore, water-heating heat pumps can be easily combined with renewable energy sources to achieve an additional reduction in the required primary energy consumption of the building;
- openness of the European market to Japanese manufacturers, which are the current world leaders in DHW CO_2 heat pumps. It was found that COPs up to 5.1 can be accomplished by heating water from 16 °C to 65 °C at the external temperature of 24 °C (Hashimoto, 2006).

Adriansyah (2001) suggested the use of R744 heat pump installations to meet both the water heating and the air-conditioning demands of large hotels in hot climates, whose contributions to their total energy consumption are respectively equal to 44% and 19% (Figure 3.2).

Figure 3.2 Breakdown of the energy consumption in a typical large hotel (< 100 rooms) in hot climates (Adriansyah, 2001).



According to Nekså (2002), an air-water CO_2 heat pump unit consumes 75% less energy than electrical or gas-fired systems to produce tap water at 60 °C. Also, the author pointed out the R744 as a promising working fluid for space heating applications. Byrne et al. (2009) designed and compared the performance of an improved R744 heat pump unit for simultaneous heating and cooling with that of the same heat pump system using R407C for hotels, luxury dwellings and small offices. The results showed that the improved CO_2 heat pump consumes respectively about 4% more energy than the improved R407C heat pump and 13.2% less electricity in comparison with a standard heat pump in a hotel located in Paris (France). As for the outcomes in terms of TEWI, reductions from 4.2% up to 15.7% were estimated. As suggested by Calabrese et al. (2015), the rooftop heat pump solutions represent an encouraging technology for the air conditioning of large buildings and shopping centres. However, the evaluation carried out by these authors revealed that such a configuration could achieve lower COPs than HFC-based heat pumping units in heating mode, especially at air temperatures above 16 °C.

It is a well-known fact that high temperatures of the cooling medium and low temperature glide at the gas cooler side, operating conditions which can be commonly reached in cooling and heating modes, favour other working fluids over R744. Therefore, similarly to CO_2 refrigeration systems operating in warm regions, the success on the part of transcritical R744 heat pump technologies in Southern European market for high-consumptive buildings is strongly related to:

- the use of solutions for simultaneous heating and cooling applications;
- the identification of an expedient capable of increasing the energy savings of such systems substantially.

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Both aspects will lead to solutions extremely (energetically and economically) competitive with the ones currently used. This goal can be accomplished with the aid of the multi-ejector concept, as suggested by Hafner et al. (2014a). In fact, the author claimed that the multi-ejector technology is the most suitable solution for any "CO_2 only" application featuring a high refrigerant return temperature, such as heat pumps for space conditioning and high water temperatures.

The optimum geometry of an ejector belonging to an R744 heat pump with a small capacity was experimentally and numerically investigated by Banasiak et al. (2012). A maximum growth in COP by 8% was obtained in comparison with a cycle using a conventional expansion device. Minetto et al. (2013) experimentally mapped the performance of a CO_2 heat pump for domestic space heating and air-conditioning and employing an ejector for expansion work recovery. According to the experimental results collected by Banasiak et al. (2015a), the mass flow rate of the primary fluid is significantly affected by the inlet temperature and inlet pressure, which also influences the pressure lift (i.e. pressure difference between the diffuser and the evaporator) substantially. The adoption of an ejector as an expansion work device allows a CO_2 heat pumping to equal the energy consumption of a R410A unit, as demonstrated by Minetto et al. (2016). The authors did not take into account the benefit of the ejector for the tap water heating. The system schematized in Figure 3.3 and 3.4 and used for air-conditioning and space heating applications in Northern Italy results in an annual energy saving of about 15% over a conventional solution (Minetto et al., 2015b).

Figure 3.3 Schematic of a R744 heat pump system for tap water heating and equipped with an ejector (Minetto et al., 2015b).

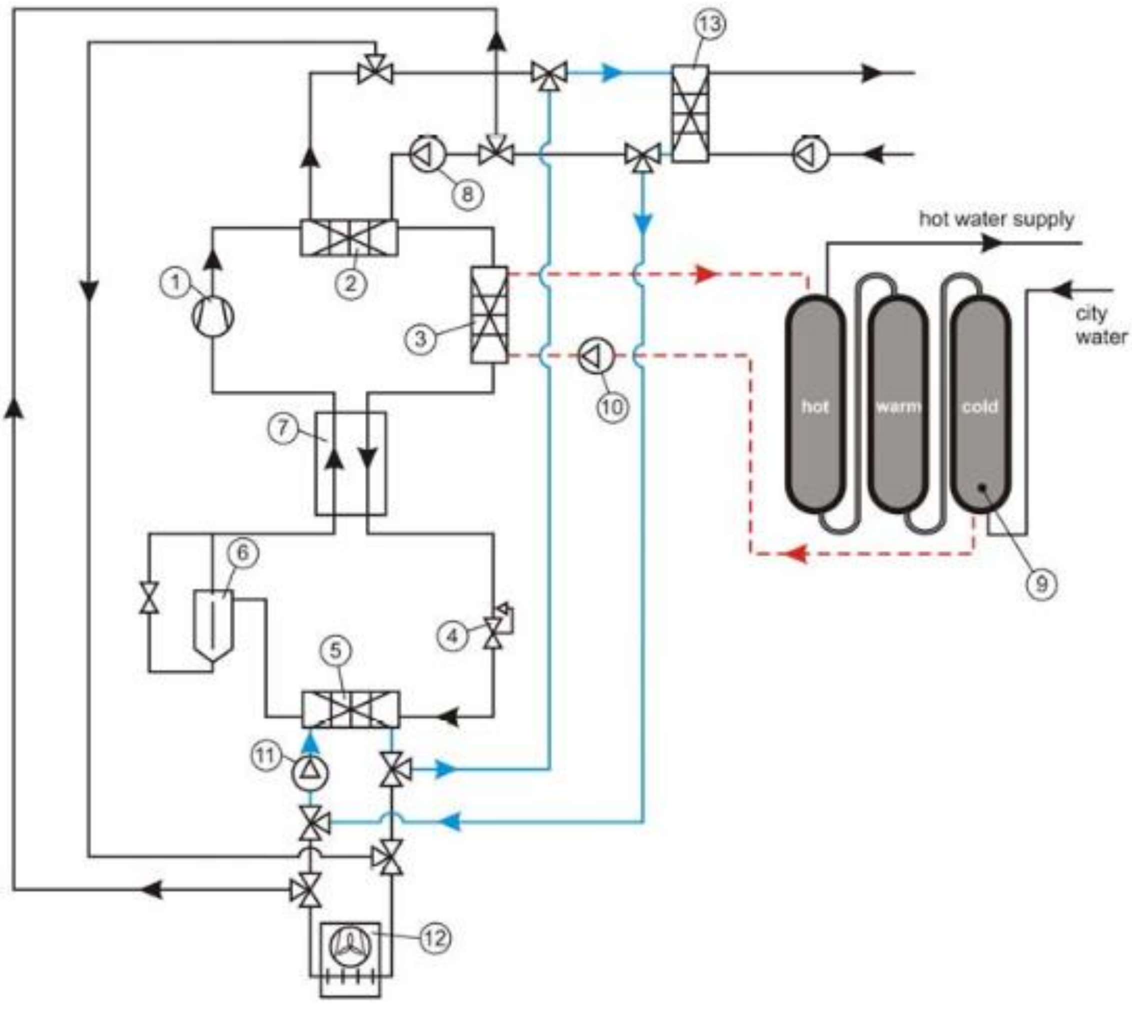

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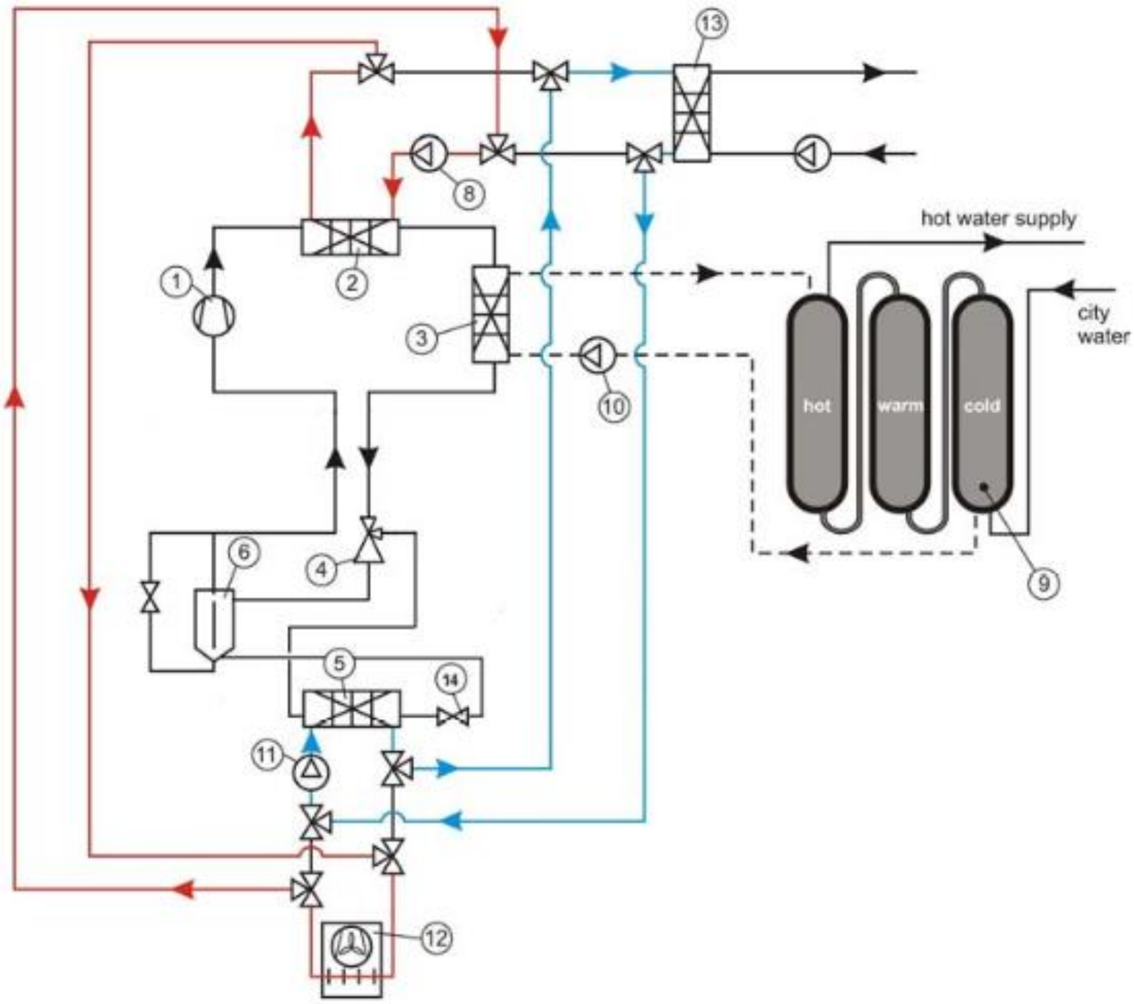
Figure 3.4 Schematic of a R744 heat pump system for space cooling and equipped with an ejector (Minetto et al., 2015b).



As regards the R744 heat pump units based on the multi-ejector, Boccardi et al. (2016) made an experimental performance comparison between a basic and a regenerated "CO_2 only" air-to-water heat pump system with an expansion valve. The authors concluded that further investigation on multi-ejector based units for air-conditioning applications are needed. At a later time, Boccardi et al. (2017) experimentally implemented a sensitivity analysis for a transcritical CO_2 heat pump solution outfitted with a multi-ejector module with respect to the ejector area ratio, compressor frequency (30 Hz ÷ 60 Hz) and outdoor temperature (i.e. -15 °C÷12 °C). The outcomes revealed that the optimal performance of the ejector does not occur at the best performance in relation to COP and heating capacity. This entails that such a solution can still be significantly enhanced as the ejector design is more accurately assessed. The investigations by Boccardi et al. (2016, 2017) suggest that it is still necessary to properly transfer the current knowledge regarding multi-ejector R744 supermarket refrigerating plants to reversible heat pumping systems. In addition, the energy, economic and environmental advantages associated with the adoption of this solution over HFC-based systems still need to be exhaustively proved. This target has to be achieved with the aid of both laboratory data and field measurements in order to remove all the technological and non-technological barriers and raise the confidence in multi-ejector based CO_2 solutions. This would allow to promote and sustain the diffusion of such systems, especially in high-demanding buildings located in warm regions for which the achievable energy, economic and environmental savings are expected to be even more emphasised. As a final remark, the

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advantages related to the integration of direct heating and cooling fan coils and air curtains on the part of reversible R744 heat pumping units also need to be assessed, especially when it comes to the aforementioned applications.

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4 Conclusions and Future work

Under the pressure of an ever-growing eco-friendly attitude as well as of ever-strict legislative acts, transcritical CO_2 supermarket refrigerating systems in Europe have experienced tremendous technological developments since the revival of this refrigerant around 1990. Also, these technologies presented an increase in energy efficiency up to 25% and a drop in their equipment cost by 30% between 2008 and 2016 (Shecco, 2016). Further falls in cost are supposed to be obtained by adopting "fully integrated" solutions in relation to HFC-based systems. Consequently, the market share of the multi-ejector based R744 supermarket refrigeration systems is expected to be equal to 50%-80% for new installations in 2020 (Hafner, 2015).

As presented in this work, the available theoretical and experimental results have revealed that multi-ejector concept is continuously pushing the so-called "CO_2 equator" southwards as regards supermarket applications. This energy efficiency limit was located in the northern shore of the Mediterranean in 2013 (Shecco, 2016). Also, this technology is already being commercialized with great results even in warm regions. On the other hand, a remarkable brake on the full penetration of such HFC-free technologies into European market, especially with respect to Mediterranean region, is put by some remaining non-technological barriers, such as the shortage of trained installers and service technicians, and the lack of confidence in such solutions. As regards reversible R744 heat pumping units, the current situation is even more dramatic. This is because, besides the presence of the aforementioned barriers, the multi-ejector concept still needs to be properly transferred from commercial refrigeration applications. In order to overcome these drawbacks, MultiPACK was established in October 2016. MultiPACK is a European project funded under the Horizon 2020 Research and Innovation Programme (Grant Agreement number: 723137). This project aims at building confidence in integrated heating, ventilation, air-conditioning and refrigeration (HVAC&R) packages based on the CO_2 technology, as an alternative to F-gases, installed in high energy-demanding buildings. The introduction of these new energy-efficient units, in addition to complying with EU regulations and reducing the impact on the environment, should decrease the specific energy consumption by more than 25% compared to HFC-based systems, while also reducing the total cost of ownership. Confidence will be built by running demonstration tests at six commercial sites at no expense for the owners. The principal target is Mediterranean Europe, where the warm climate constitutes a significant challenge for heat pumping and refrigeration technologies. During the project the performance, durability and reliability of reversible HVAC & DHW (heating, ventilation and air-conditioning & domestic hot water) CO_2 packs including multi-ejector blocks and thermal storage modules will be assessed, to secure the technological maturity of the packaged units by providing maximum possible modularity and scalability, as well as remote monitoring and control. Furthermore, MultiPACK also aims at refining the design and control of multi-ejectors according to the specifics of end-users, as well as evaluating the performance, durability and reliability of multi-ejector blocks. Similar verifications will be performed with respect to integrated supermarkets packs.

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Nomenclature

Symbols, abbreviations and subscripts/superscripts

AC	Air-conditioning
COP	Coefficient of Performance [-]
DHW	Domestic hot water
GWP	Global warming potential $[\mathrm{kg}_{\mathrm{CO}_{2,\mathrm{equ}}} \cdot \mathrm{kg}^{-1}_{\mathrm{refrigerant}}]$
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	Heat pump
HVAC	Heating, ventilation and air-conditioning
HVAC&R	Heating, ventilation, air-conditioning and refrigeration
HX	Heat exchanger
LT	Low temperature
MT	Medium temperature
p	Pressure [bar]
$\dot{Q}_0$	Cooling capacity related to air-conditioning unit [kW]
$\dot{Q}_C$	Heat capacity for space heating [kW]
t	Temperature [°C]

Greek symbols

Δ	Difference

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