HIGH EFFICIENT INTEGRATED CO_2 REFRIGERATION SYSTEMS WITH EJECTORS AND PIVOTING COMPRESSOR ARRANGEMENTS

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ABSTRACT

Equipment manufacturers of refrigeration units are facing challenges related to the legislative requirements forcing them to implement less conventional refrigerants with lower Global Warming Potential (GWP). The newly introduced next generation of hydrofluorocarbons (HFCs) with ultra-low GWPs do have a very short (atmospheric) lifetime, however, the decomposing products are highly toxic in combination with water, short life HFCs and their blends do not represent a safe and sustainable alternative.

CO_2, a natural working fluid applied since the early days of refrigeration, has demonstrated to be an energy efficient and environmentally benign alternative. Design effort has to be made to develop affordable high efficient integrated refrigeration systems applicable in high ambient temperature areas. One way to reduce size and costs is to adapt the number of compressors at the various suction groups. Another enhancement possibility is the utilisation of the normally unused expansion work by applying ejectors.

The article will describe how enhancement measures like ejectors and pivoting compressors will influences the energy efficiency and can help to downsize systems. Cold energy storage is also an interesting feature, supporting the refrigeration systems with accumulated cooling capacity, applicable during peak capacity periods, without additional compressors.

Keywords: CO_2 refrigeration systems, pivoting compressors, commercial refrigeration, cold energy storage

1. INTRODUCTION

A new era for the refrigeration society has started after the Kigali amendment [UNEP, 2016]. Since current working fluids are not the preferred solution of the end-users in the near future anymore changes are required and successful developments have to be performed to get refrigeration technology out of the current negative focus area and become much more sustainable. At the moment there are two potential directions companies within the refrigeration sector can choose if they want to be in the business 10 years from now.

On one hand, they might continue with their current design philosophy and replace the high GWP fluids with lower GWP fluids and partly with new ultra-low GWP fluids. The intermediate detour by applying at least stable (HFC-152a, HFC-32, etc.) fluids requires in the first run only a careful safety concept, due to flammability issues. However, the ultra-low GWP fluids are a dead-end scenario, due to the lack of knowledge related to the health, safety and environmental risks related to the decomposing products of these short living substances (U.S.Dep.H&HS, 2005; Hurley et al. 2008; Solvey 2012). How cautious authorities are can be seen by the example from Germany where the maximum Occupational Exposure Limits for 2,3,3,3-Tetraflourpropen (HFC-1234yf) is only 200 ppm (BMI 2016).

There is an increasing number of innovative companies which already have chosen the opposite direction, away from HFCs by exclusively applying natural working fluids in their products. These vendors are able to concentrate their efforts and investments in further developments and improvement of long-lasting products, not facing the risk of legal restrictions in the near future nor wasting time and resources adapting old units to short living cocktails.

As shown in numerous demonstration projects where HFC equipment has been replaced by CO_2 systems (Santoso 2016 and Uto 2016) the alternative system can reduce the energy consumption by up to 30 %, even in hot ambient temperature (HAT) regions. To be able to outperform current HFC based refrigeration units, also with respect to initial costs flexible suction group configuration can contribute to reduce the number of installed compressors and thereby initial costs. End-users, i.e. owners of supermarket chains and high performance building, are looking for integrated refrigeration units applying CO_2 as working fluid. To avoid high installation cost and to improve the compactness of the refrigeration packs with various annual cooling demands of various suction groups, Hafner et al. (2016) recommended to enable a switching (pivoting) of the compressor suction towards the different suction groups. Figure 1 shows the principle of pivoting 4 of 6 compressors. Depending on the status of the on/off valve upstream of the compressors (x2-x5) they are either connected to the MT- or AC-suction group. In case the shut-off valve is closed, the compressors are connected to the MT-suction group via the check valve. If the valve is open, the pressure level of the AC suction group is higher and the check valve closes the connection to the MT part. The compressors do have a common discharge manifold connected to the various heat rejection and heat recovery devices downstream of the compressors.

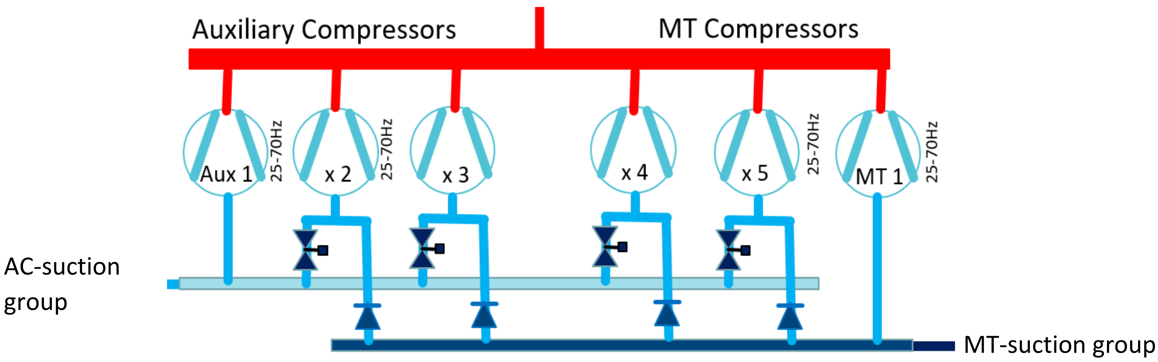

Figure 1: Pivoting 4 of 6 compressors.

The example scenario shown in Figure 2 demonstrates and indicates that the MT compressors and parallel/auxiliary compressors have to be utilized in a more flexible way in future applications, since the total number of compressors is in close relation to the cost of a rack. At low heat rejection temperature (below 10°C) the parallel compressor is not in operation, the flash gas bypass valve throttles the flash gas from the separator pressure level to the evaporator pressure level. All the vapour has to be compressed by the MT compressors. At a certain opening level of the flash gas bypass valve the smallest parallel compressor can start its work, indicated with the red line in Figure 2. Now the MT compressors have a slightly reduced mass flow rate. Due to the low high side pressure, the ejectors are able to deliver liquid and vapour from the evaporator pressure level to the separator pressure level, however, the amount is limited due to the reduced availability of expansion work. At heat rejection temperatures between 15 °C and 20 °C the pressure level inside the separator can be increased, the ejectors (green line) support the parallel compressors by gradually unloading the MT compressors more and more. At the same time the amount of flash gas (black line) is increasing towards higher gascooler exit temperatures. In this example, the ejectors reach they design point when the ambient temperature is around 30 °C. Now the pressure difference between the separator and the evaporator could be further increased to optimize the energy efficiency of the system, and to boost the capacity of the evaporators. In this temperature region the amount of refrigerant through the MT compressors is equal to the mass flow rate through the parallel compressors (red and blue lines are crossing).

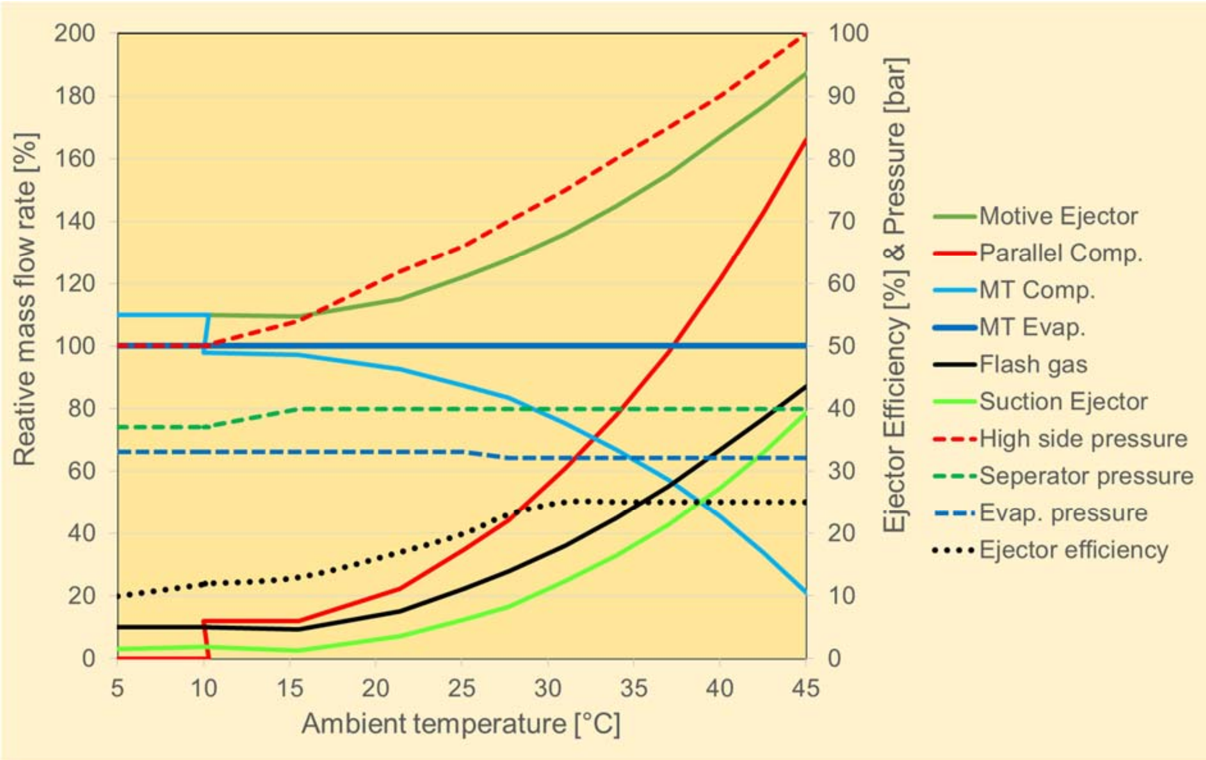

Figure 2: Scenario; relative mass flow rates of the ejector supported parallel compression unit, without AC.

Since the amount of flash gas is further increasing at elevated ambient temperatures and the ejectors are able to utilize ~25 % (up to 35 % are possible as reported by Banasiak et al. 2015) of the expansion work to pre-compress the vapour from the MT evaporators the MT compressors are further unloaded. At 45 °C ambient temperature, the required mass flow rate through the MT-compressors is only 10 % while the parallel compressor have to handle 160 % of the relative mass flow rate with respect to the MT evaporator. The total mass flow rate circulating through the high pressure side is indicated with the dark green line showing the relative mass flow rate through the motive nozzles of the ejectors, responsible to maintain the optimum high side pressure.

Examples on how such flexible and compact systems can be made are shown in this article.

2. SYSTEM SOLUTIONS

Integrated system solutions are characterised by the ability to provide most of the heating and cooling demands within a certain area or part of a building, even possibly export surplus heat or cooling towards buildings or industrial processes in the neighbourhood.

As shown by the example in Figure 2 the capacity requirement of the various compressors changes on one side due to the variations in the ambient temperature on the other side due to variations of the cooling load and or heating request, therefore capacity control measures have to be implemented to maintain a certain evaporation temperature within a certain limit and to avoid start/stop operation of the compressors. To be able to provide the required cooling/heating capacity at various capacity levels a range of compressors is commonly implemented in most industrial/commercial CO_2 systems. A wide-range single CO_2 compressor as initially developed at SINTEF and NTNU in cooperation with Obrist Engineering (Hafner et al. 2013) would reduce the number of compressors, especially where space in machine rooms is limited, such as on board of marine vessels. The latest developments from leading compressor manufacturers enable vendors to build compact refrigeration packs by implementing CO_2 compressors with volume flow rates of up to ~50 m^3/h. However, also the part load operation has to be taken care of. Therefore it is necessary to carefully define the size of the various compressors at the different suction groups.

Figure 3 shows a simplified system circuit containing a low temperature (LT) suction group, a medium temperature (MT) suction group and a parallel compression suction group which can be utilised to provide direct AC at adapted AC evaporation temperatures. The ejectors are controlling the high side pressure while supporting the parallel compressors, i.e. increasing the number of operation hours, by unloading the MT compressors due to pre-compression of vapour from the LT Receiver to the MT Separator. The suction group of each MT and parallel compressor can be pivoted by a 3 way valve.

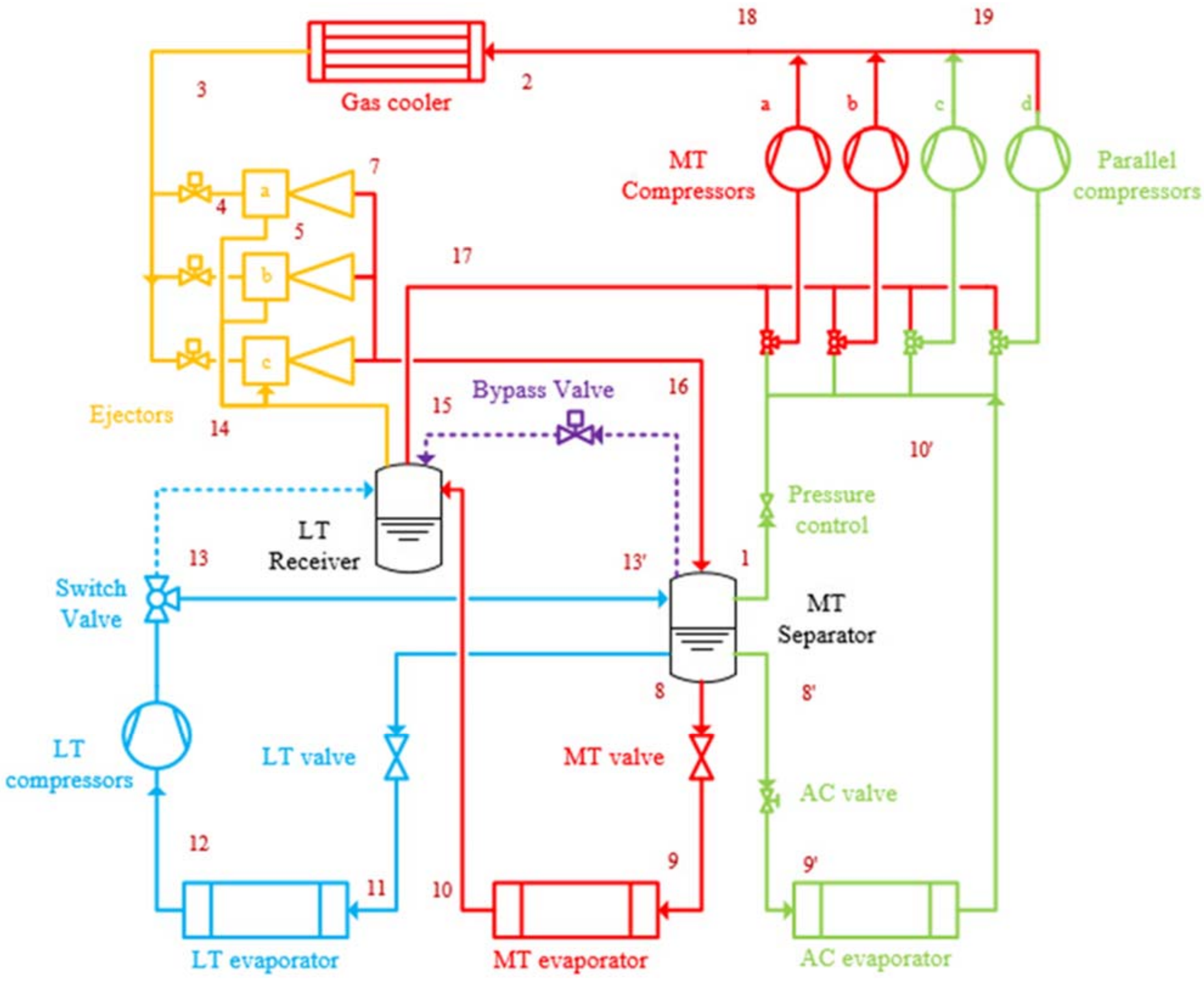

Figure 3: Simplified system circuit containing a LT, MT and parallel compression suction group.

An example of how a 'gap-free' control of the cooling capacity between 8 % and 100 % of the MT cooling load can be realised with 4 different compressors is shown in Figure 4. Two compressors (comp. 1 and 2) are equipped with frequency controllers. The compressors do have the following displacement at 50 Hz: Comp. 1 = 4,74 m^3/h, Comp .2 = 8,92 m^3/h Comp. 3 = 13,84 m^3/h and Comp. 4 = 11,62 m^3/h.

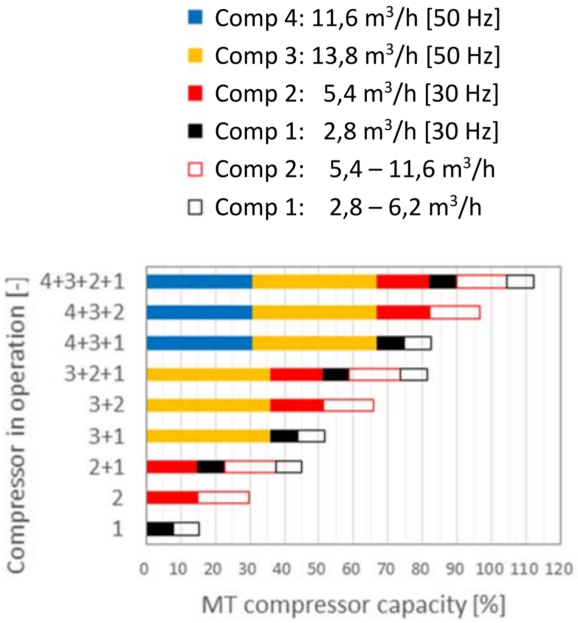

Figure 4: Compressor arrangement with 4 compressors enabling a capacity control from 8% to 100%.

This arrangement fits very well for installations in Nordic climate conditions, where simple booster systems are typically applied.

In most other climate conditions, a parallel compression arrangement as shown in Figure 3 is applied, since the amount of flash gas is much higher during the warm period of the year and an efficient integration of the AC function can be provided.

Figure 5 shows the possible capacity variations of the system architecture shown in Figure 4. Some of the compressors can be applied as parallel compressors as required to maintain the to MT separator pressure. These compressors compress the flash gas, allow efficient integration of AC load, and further compress the vapour delivered by vapour ejectors unloading the MT compressors.

In the topmost case, only the smallest compressor is used on the MT suction group. It represents a high ambient temperature summer load condition, i.e. the amount of flash gas is high, the AC load is high and the ejectors are able to remove most of the vapour from the low pressure receiver upstream of the MT compressors (as shown in Figure 2 at the highest ambient temperature conditions).

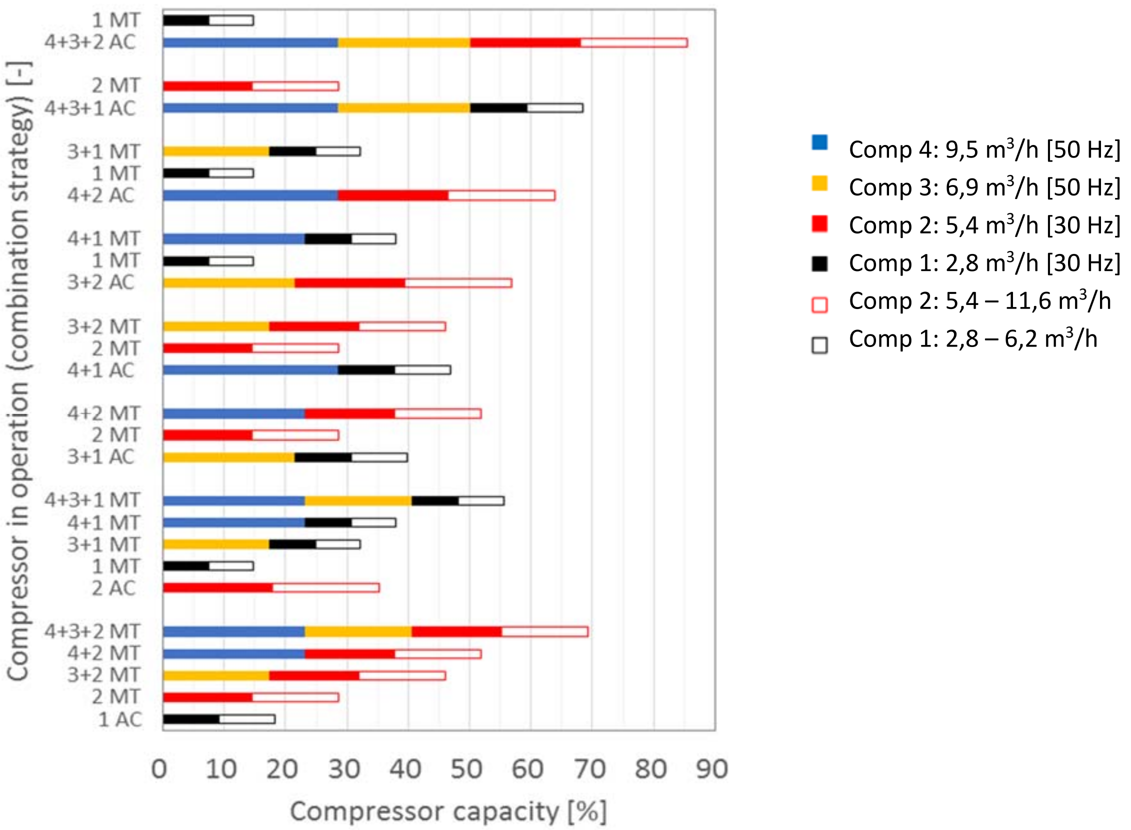

Figure 5: Compressor arrangement with 4 compressors enabling a capacity control from 8% of the total cooling capacity. Two compressors with frequency drives (30-65 Hz); AC + MT section.

The smallest MT compressor is applied to maintain the MT suction pressure and to balance small capacity changes due to defrosting of cabinets etc. Downwards in the diagram of Figure 5 the load of the parallel compressors is continuously reduced, therefore the second MT compressor takes over for the smallest MT compressor which is pivoted from the MT to the AC suction group. In the third arrangement compressor 3 and 1 are attached to the MT suction group. While in the fourth configuration compressors 4 and 1 are the ones performing the MT suction duty. The example at the bottom indicates the configuration for a late autumn and spring climate condition (see also Figure 2), i.e. only the smallest compressor is applied to remove the flash gas downstream of the high side pressure control device.

Integrated commercial refrigeration systems for Southern Europe

Figure 6 shows a proposed high efficient integrated system for supermarkets located in Southern Europe or the Middle East. The system is also able to provide a certain heating demand during the winter season due to its heat pump function.

The LT compressors are maintaining the suction pressure of around 17 bar for the attached LT cabinets and cold storage rooms. The LT evaporators are operated without superheat, to improve the performance and reduce the losses during heat transfer. In case of overflowing liquid, the suction accumulator upstream of the LT compressors collects the liquid refrigerant, which is evaporated by the integrated (or external) heat exchanger, i.e. it further subcools the liquid supplied to both the LT- and MT evaporators. The discharged fluid of the LT compressors should be de-superheated before entering the AC compressor suction group, redirected via the flash gas bypass valve when there is no AC compressor operation. Connecting the LT compressors to the AC compressor suction group allows to further extend the operation hours of the AC compressors, however, both LT and AC compressor have to be designed for higher discharge pressures (LT) and higher suction pressures (AC) to achieve high energy efficiencies of the system.

The pivoting principle, described above is applied to most of the MT and AC compressors. In given example, only one compressor is connected directly to the AC and MT suction group. This configuration allows to reduce the total number of frequency converters required in the system. It might be possible to use only one frequency converter within the pivoting compressor group.

The heat rejection and heat recovery part of the system is divided into two sections. The right-hand side is devoted to operations outside the summer season, with the gascooler designed to reject the heat form both LT and MT cooling demands. In case of domestic hot water demand the heat recovery has priority, i.e. less or no heat is rejected to the ambient. The left-hand side is devoted to the extreme climate conditions occurring during the hottest and coldest days of the year. The heat recovery unit provides heated water to the heating system of the building during winter time. The exterior heat exchanger is operated as an ambient air evaporator, i.e. air is the heat source for the heat pump function. The AC Multi Ejector sucks all the mass flow rate from the exterior heat exchanger. Since the ambient temperatures in these regions are seldom below 0 °C, the pressure in the separator providing the liquid to the evaporators can be kept above 38 bars, allowing a safe supply of liquid refrigerant also during heat pump operation. When AC is required, the exterior heat exchanger is the main heat rejection device (gascooler) for the parallel (AC) compressors. Beside evaporative cooling (Visser 2015) an auxiliary heat sink could be applied to further reduce the refrigerant temperature upstream of the high side pressure control devices, for example Multi Ejectors, during the warmest hours of the day. In the shown example, the water of the fire water tank is applied as auxiliary heat sink. The temperature of the fire water can be reduced during night hours with a dry cooler, e.g. by recycling the condenser of the previous HCFC system, which is successfully replaced by the integrated CO_2 unit.

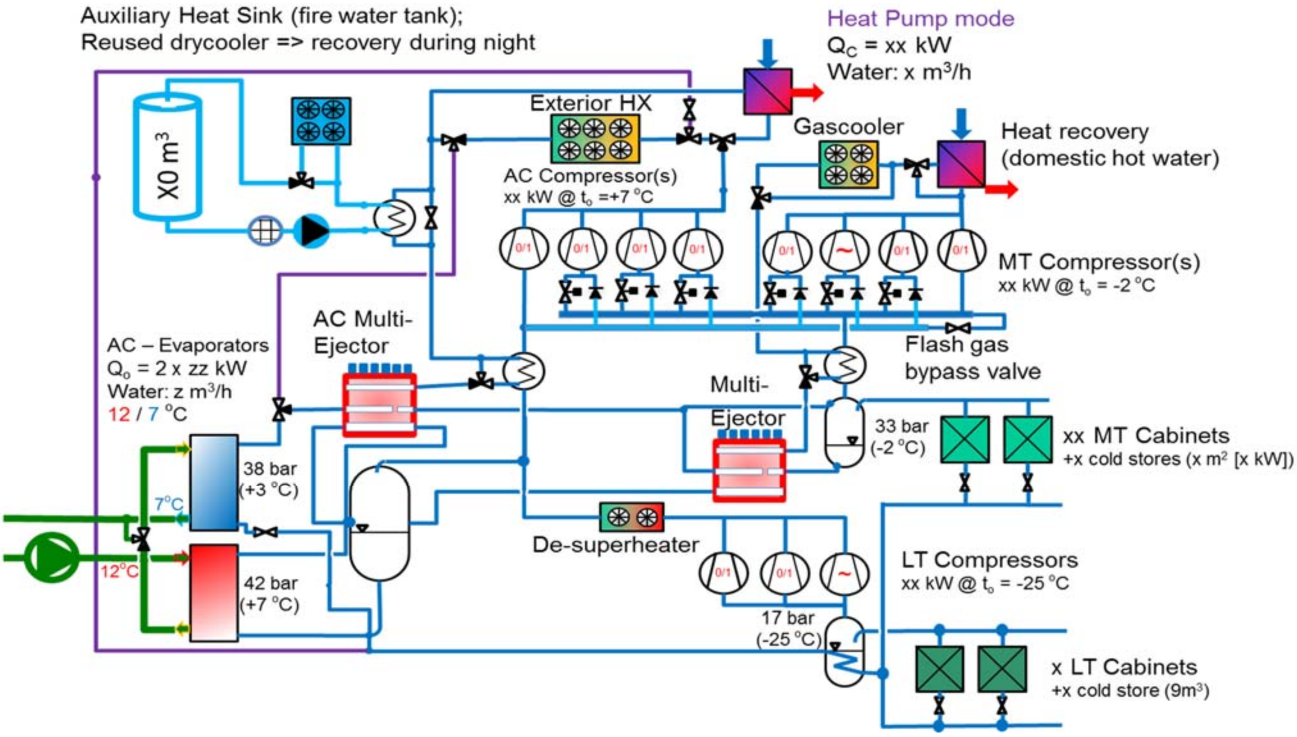

Figure 6: Integrated CO_2 refrigeration Pack for South European locations with LT and MT cooling loads, hot water demand, heating & cooling demand for the building and an auxiliary heat sink.

The innovative integration of the ice-water cooling evaporators (lower left-hand side of Figure 6) in combination with the AC Multi Ejectors allows an elevated suction pressure of the AC compressors. The evaporators are divided into two sections. The first sections is connected to the separator tank at 42 bar ($t_o \approx +7$ °C). The liquid refrigerant is supplied by gravity and allows the pre-cooling of the 12 °C coolant returning from the building. If more cooling capacity is required the second evaporator is enabled to further reduce the temperature of the coolant to 7 °C. The suction pressure is now 38 bar ($t_o \approx +3$ °C) due to the usage of the AC Multi Ejectors, which are able to suck all the vapour out of the second evaporator and supply it back to the separator where the AC compressors maintain the pressure level.

Since the revival of CO_2 as refrigerant initiated by Lorentzen et al. (1992), it is known that the superheating of fluid flows out of evaporators is not beneficial for the performance of CO_2 refrigeration systems, due to its high $\Delta p/\Delta t$ ratio and the high heat transfer coefficients that can be obtained. The habit of maintaining the request for a superheat out of heat exchangers, even for CO_2 systems, has led to system configurations for example for commercial refrigeration units that apply the same evaporation temperatures as for HFC systems. However, for chilled food applications with a CO_2 refrigeration unit an evaporation temperature of -10 °C means that the suction pressure must be around 26.5 bar. New adapted system configurations, as shown above, taking into account the safe handling of liquid downstream of evaporators and the high heat transfer performance of CO_2 can provide the required cooling capacity without superheating at evaporation temperatures of -2 °C with a corresponding elevation of the suction pressure to 33 bar. This has a significant effect on the number of defrost cycles required in the chilled food cabinets.

Proper handling of liquid refrigerant and lubricant downstream of the evaporators is crucial to ensure a safe operation of the compressors. There are several ways to manage the direction of the liquid flow. Ejectors, driven by the normally lost expansion work, are one way to return overflowing liquid back to the separator on the upstream side of the evaporators. Another flow direction of the liquid and lubricant can be implemented if the system has a continuously LT cooling demand. However, the LT compressors have to be able to return all the lubricant transported into the LT section back to the compressors of the MT- and/or AC suction group.

Integrated commercial refrigeration systems for Northern Europe

A proposal for the general outline of an integrated CO_2 system for locations with a high demand of heating at different temperature levels and generally low ambient temperatures is shown in Figure 7.

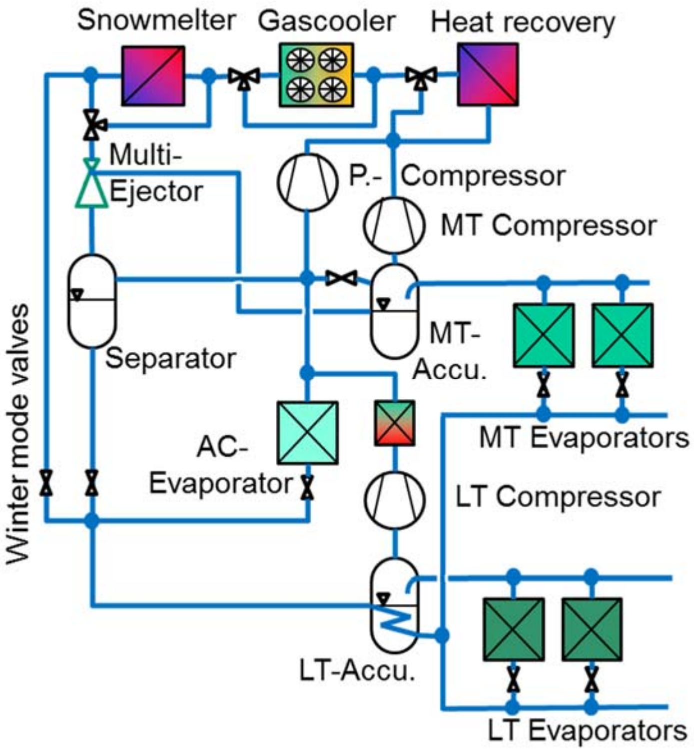

Figure 7: Integrated system for Nordic regions.

The pivoting principle as describe above can be applied here as well; however, it is not implemented into the flow circuit to keep it simpler. Heat rejection can take place at three different temperature levels. Downstream of the compressors the highest temperature level can be achieved, applicable to high temperature heating such as for domestic hot water. This heat exchanger can be active also during the warm period of the year.
The second heat exchanger downstream of the compressors is the air-cooled gascooler, enabling a proper heat rejection of the entire heat to the ambient during summer. During the cold period, the airside gascooler can be bypassed most of the time, since the available heat can be utilised in the first and third heat exchanger downstream of the compressors. The main purpose of a third heat exchanger can be preheating of domestic hot water or providing heat to the outdoor floor heating system, normally using direct electrical heating to keep the entrance and delivery area free of ice.

Low ambient temperatures can be a challenge for traditional CO_2 booster systems, when the CO_2 temperature downstream of the heat rejecting devices becomes lower than 5 °C. Since this temperature represents the saturated temperature inside the separator at 40 bar. If the refrigerant temperature upstream of the separator drops below the saturation temperature, the pressure inside the separator is reduced due to partial condensation of the vapour inside the separator. Therefore, extra safety measures have to be taken and implemented to protect the separator pressure, which secures the liquid supply to all evaporators. However, this again reminds of the pressure maintenance actions required for HFC systems. To avoid the system to be dependent on the separator pressure a so-called winter mode upgrade is proposed. When the ambient temperature is below a certain value, the separator is taken out of the main system circuit, i.e. the liquid refrigerant downstream of the heat rejection devices is directly supplied to the evaporator feeding valves, like in traditional subcritical systems. The main controller operates the total opening of all feeding valves to maintain a certain and safe high side pressure. If the amount of refrigerant in the circuit is insufficient, for example detected by continually superheated evaporator outlet conditions and the absence of a liquid level in the MT-accumulator, liquid refrigerant is supplied from the bottom part of the separator back into the main circuit. On the other hand, if the refrigerant level is too high, vapour is rejected into the separator by opening intervals of one of the motive nozzle valves inside the multi ejectors, or another high-pressure control device upstream of the separator.

If more heat is required due to the building structure or if export possibilities towards neighbours are present, energy wells (Hafner et al. 2014) can be employed to supply additional external low temperature heat into the system. Since the temperature level in the ground is above to the freezing point of water, an efficient integration into the MT evaporator loop can be done.

Heat storage devices (water or PCM reservoirs) are advisable in such systems to allow the CO_2 system to operate at optimum conditions most of the time. Balancing of the daily heat demand variations should take place by applying storage devices, such that the system avoids to 'hunt' set-point movements. Peak heat requests are then supported from the storage devices, while the CO_2 system charges them continuously.

Integration of direct AC + heating

Figure 8: Direct heating and cooling fan coil unit inside a Supermarket (Girotto 2016).

Girotto (2016) describes the current challenges when applying integrated AC and heating based on water circuits connected to the refrigeration unit. When water is used as the energy carrier several heat exchangers are involved, each of them introducing losses, which reduce the total efficiency of the heating and cooling system. Water itself is corrosive, i.e. measures to prevent corrosion have to be taken with a corresponding reduction in efficiency due to changes of the thermophysical and fluid properties of the water/inhibitor mixture. The water circuit does have a significant share of the total investment costs.

When CO_2 is used as the working fluid in refrigeration systems, it permits to apply direct cooling and heating fan coils installed inside the building, as the roof installation shown in Figure 8. Also the air curtains, mainly installed in the entrance area and the large delivery ports, can be designed in the same way. These kind of unit do not require space for water reservoirs and pump arrangements. The total cost of the heating and cooling equipment can be reduced as well as the energy demand to provide comfort and secure area temperatures during all seasons.

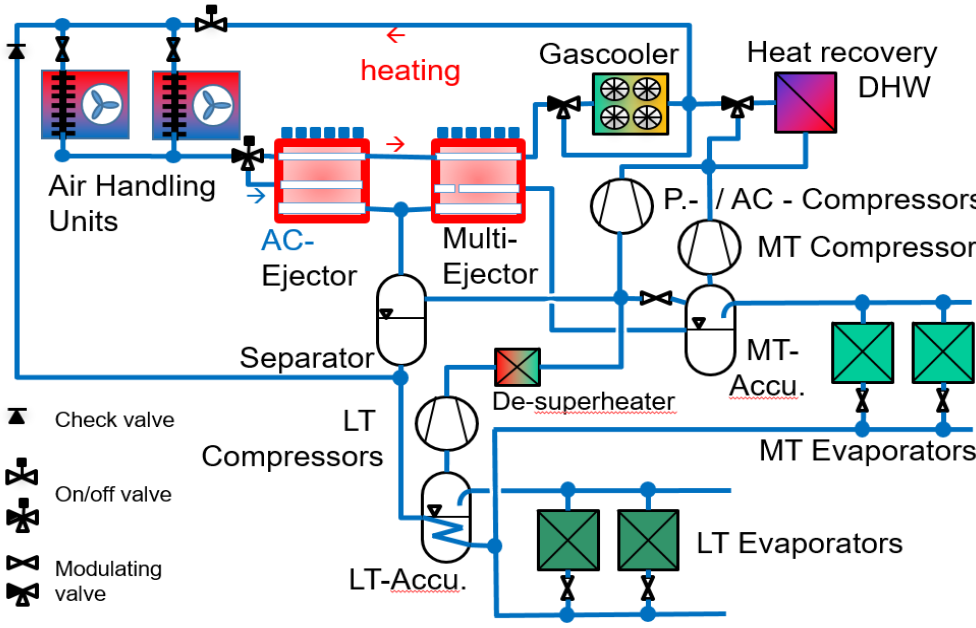

Figure 9: Integration of direct heating and cooling air handling units in CO_2 commercial refrigeration units.

There is also a significant reduction of the time required to implement the HVAC installations. However, due to the high operating pressures present inside the public part of the building, special attention has to be given to the craftsmanship when installing the CO_2 pipes inside the building. The applied heat exchanger coils must be designed for dual operation.

Figure 9 shows a possible way of integrating the heating and cooling devices into the CO_2 circuit. During summer operation, when AC is required, the AC ejectors are able to circulate the required amount of refrigerant through the evaporators of the air handling units at various locations inside the building. When heating is demanded inside the building, the main outside air cooled gascooler is bypassed, and heat is rejected directly by the air handling units (fan coil or air curtain).

This principle represents a viable solution for small shops as well as large commercial building installations.

3. SUMMARY

A remarkable development of CO_2 refrigeration technology has taken place since the revival of the refrigerant in the late 1980s. The development has led to efficient CO_2 systems and their successful introduction into the market. Additionally, it inspired the development of other innovative technologies that focus on improving the energy efficiency and reducing the total cost of ownership by applying pivoting compressor arrangements.

The integration of expansion work recovery devices like ejectors allows today's CO_2 commercial refrigeration systems to outperform HFC units on annual energy consumption in any climate region. The integration of further functions into the centralised refrigeration unit will be a key success factor for these sustainable vapour compression systems replacing HCFC and HFC systems globally.

The engineers spreading CO_2 technology should remember when designing all of the integrated functions, that the fluid properties are an asset, not a hindrance. Therefore, all CO_2 evaporators should be operated without superheat, heat recovery should be employed whenever there is a heat demand and domestic hot water production should be a natural feature of the systems.

Heat exchanger manufactures are able to provide safe air/CO_2 heat exchangers, enabling a direct integration of heating and cooling functions into the building envelope without costly water loop solutions.

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