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CO_2 refrigeration technology: possible innovations

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ABSTRACT

CO_2 as a working fluid in refrigeration and heat pumping systems is currently entering more and more sectors, due to its unique characteristics and safety advantages. As a non-flammable refrigerant, there are very few restrictions to apply this natural working fluid in domestic and industrial applications.

An important issue, when introducing CO_2 refrigeration technology, is to understand that the thermodynamic and fluid dynamic properties are different compared to conventional refrigerants. To enable energy efficient system configurations, just a refrigerant drop-in design approach will fail. The main advantages of applying CO_2 as a working fluid are the high working pressure level, excellent heat transfer properties, the ability to achieve high temperature lifts, and high compressor efficiencies enabling energy efficient and safe installations.

The integration of ejectors in various configurations opens for additional functionalities. Based on the description of state of the art system configurations, possible innovative system improvements are described, such as ejector-supported AC production or ejectors enabling additional evaporation temperature levels.

Understanding of potential design improvements and their impact to cost and energy demand are the first step to get new technology developed and to create a market interest.

Keywords: R744, CO_2 heat pumps, Ejectors, cold thermal storage

1. INTRODUCTION

After the initial development of modern CO_2 refrigeration technology by Gustav Lorentzen's team (Lorentzen 1992) in the late 80s, more than 30 years ago, these kind of alternative systems have entered important refrigeration and heat pumping sectors. The most successful implementations are those where the system design has been adapted to the special thermodynamic and transport properties of CO_2. Compared to traditional working fluids, CO_2 is the only long-term non-flammable working fluid not affecting the ozone layer and global warming. During production, no environmentally unfriendly emissions occur, which is the reason for having the lowest direct environmental impact of all refrigerants. The safety level is the highest possible, A1.

The low critical temperature of 31.1 °C means that the practical upper temperature level for achieving condensation inside a condenser is around 28 °C. Therefore, heat rejection at elevated ambient or return temperatures takes place in the supercritical region with a transcritical process. The pinch point, i.e. the lowest temperature difference between the CO_2 and the heated fluid, should be at the refrigerant side outlet when rejecting heat in a gascooler at gliding temperatures. Due to the gliding temperatures inside the gascooler high temperature lifts can be achieved, which is beneficial for example for hot water heat pumps. At low heat rejection temperatures the refrigeration process of a CO_2 system is similar to traditional working fluids, which is also the case for the heat uptake inside the evaporator.

The relative high pressure levels, the critical pressure is at 73.8 bar, inside a CO_2 refrigeration or heat pumping system are beneficial with respect to the compactness of the units. When comparing the gas density to

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traditional working fluids it is relatively high. However, this means also that the volumetric refrigeration capacity is high (four to ten times higher than for traditional refrigerants) and the required stroke volume in the compressor is low. At low evaporation temperatures, the difference in required compressor suction volume flow rate is significant and is a strong advantage of CO_2. The saturation/evaporation pressures above the atmospheric level are very favourable for freezing applications, as the triple point of CO_2 is at -56.6 °C and 5.18 bar. Thus, evaporation temperature below -50 °C is becoming state of the art within the process industry. The very low pressure ratio, i.e. high side pressure divided by the suction pressure, is an advantage and enables to achieve high isentropic compressor efficiencies. Another important benefit of the high pressure levels is the steep pressure curve, which means that there is a very low reduction in temperature per unit pressure drop inside the heat exchangers and refrigeration lines. A significant reduction in the pipes sizes can be seen when utilizing direct expansion systems with CO_2 compared to systems applying traditional working fluids.

The favourable fluid properties regarding heat transfer are because CO_2 has: a low viscosity, relatively high thermal conductivity (lower than Ammonia), high specific heat capacity, a high pressure level and low surface tension. The low surface tension enables boiling (effervescence) at low temperature differences. As a result, the heat transfer coefficients of CO_2 within the different heat exchangers are significantly higher on the refrigerant side compared to traditional working fluids. Therefore, it is highly recommended to redesign and adapt heat exchangers when utilised for energy efficient CO_2 heat pumping and refrigeration units.

Compared to other refrigerants, CO_2 has significant higher throttling losses. This turns out to be, on the other hand, an opportunity to implement devices for expansion work recovery. Such devices, either expanders or ejectors can contribute to improve the energy efficiency of a transcritical refrigeration or heat pump unit, especially when operated at high ambient temperatures or return temperatures from the heat rejection devices.

To achieve a high system energy efficiency, ejectors themselves must have high efficiencies at different operating conditions. Thus, the ejector design plays the key role in the system behaviour and the total energy demand.

Implementing a two-phase ejector reduces the throttling losses in comparison to a traditional high-pressure control valve and therefore the overall COP of the systems increases. Figure 1 shows a simple ejector circuit described by Elbel and Hrnjak (2008).

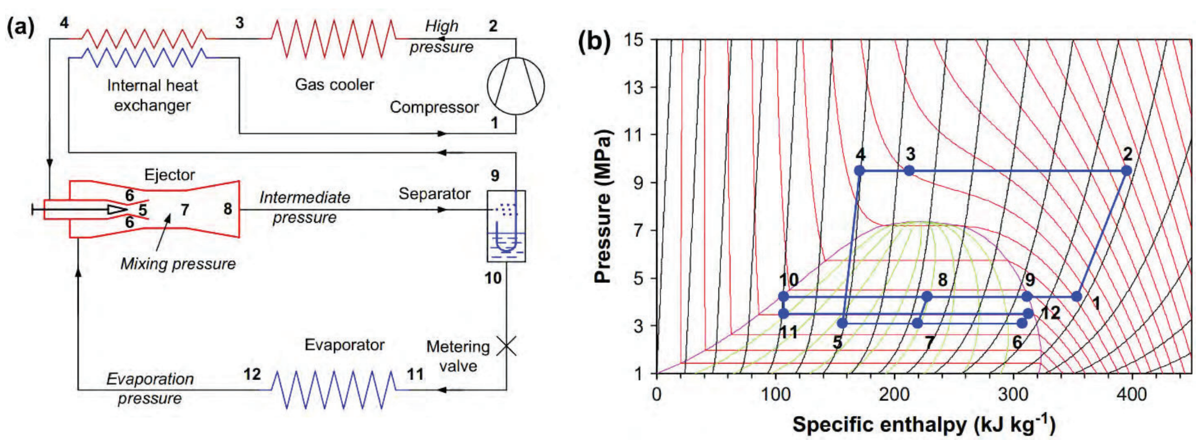

Figure 1: Component layout (a) and pressure enthalpy diagram of a transcritical CO_2 ejector system (Elbel & Hrnjak 2008)

In simple terms, the saturated vapour coming from the separator is compressed before it enters the gas cooler where heat is taken off the flow. When entering the motive nozzle of the ejector the fluid expands while crossing the saturated liquid line and flashing into two-phase flow. The suction flow coming from the evaporator is entrained into the suction nozzle due to momentum transfer. After mixing of the two flows, the kinetic energy is transferred back into pressure energy in the mixing chamber and the diffuser. Thus, the two-phase flow is pre-compressed before entering the separator and the subsequently unloading the main compressor (Elbel, 2011).

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In case of a fixed ejector geometry, as the developed Multi-ejector from Danfoss, shown on the left hand side of Figure2, it might be expected that the ejector performance will considerably decrease in part-load operation where the boundary conditions deviate from the nominal ones the ejector was designed for. As measured results, shown in the right hand side of Figure 2 (Banasiak 2015) indicates, the ejector efficiency does somehow decrease in of design operations, as the operation point deviates from the optimum high pressure set-point level. The efficiencies are shown as a function of the motive nozzle inlet conditions for the fixed geometry ejector cartridge HP125 of the Multi-ejector.

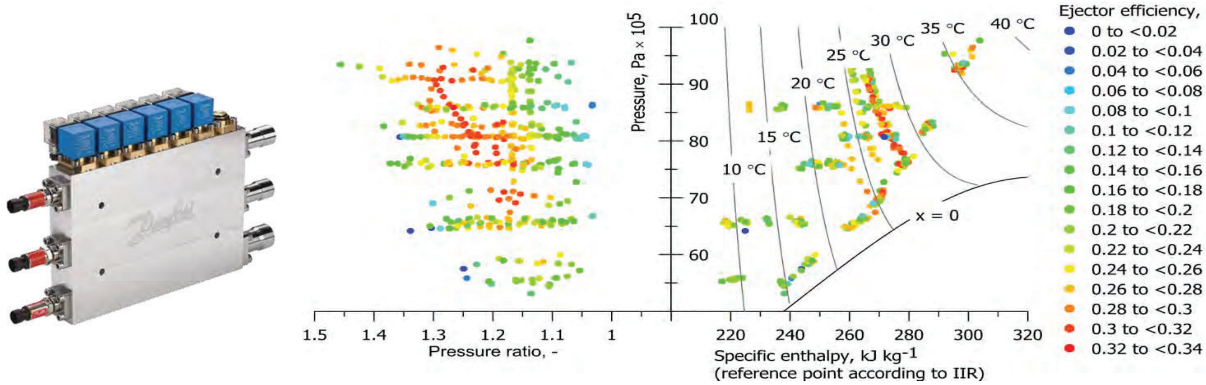
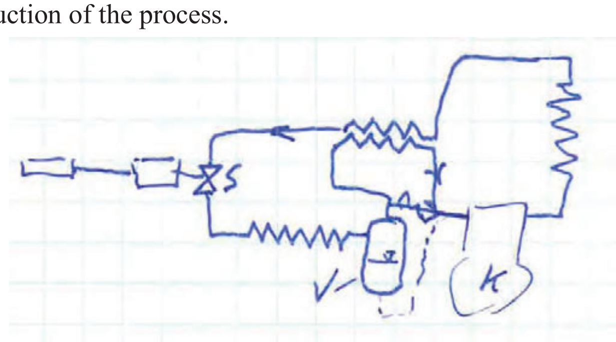


Figure 2: Left, Multi Ejector block by Danfoss (www.danfoss.com). Right, measured ejector efficiencies of a fixed geometry Multi-Ejector cartridge.

2. CO_2 SYSTEM LAYOUT

The basic structure of the CO_2 refrigerant circuit has been slightly modified since the revival of CO_2 as working fluid in late 80's and early 90's of the last century. Figure 3 shows, on the left hand side, the original drawing of the CO_2 circuit by Gustav Lorentzen. Starting the loop at the compressor [K], a gascooler follows connected to the high-pressure side of an internal heat exchanger. Expansion takes place in a high pressure control valve [S] supplying two phase fluid into an evaporator without superheat. The remaining liquid is collected and stored in a low-pressure receiver [V]. Mainly vapour and a share of liquid refrigerant plus lubricant returns to the compressor via the low-pressure part of the suction line (internal) heat exchanger. On the right hand side, a state of the art CO_2 chiller layout is shown, developed within the EU funded project MultiPACK (2018); heat recovery is implemented between the compressors and the gascooler, while the high side pressure control valve is replaced by an ejector. The liquid receiver supplies liquid refrigerant towards the evaporators of the chiller producing cold process water. Two evaporators absorb the heat from the process water at different evaporation pressure levels, which reduces the exergy destruction of the process.



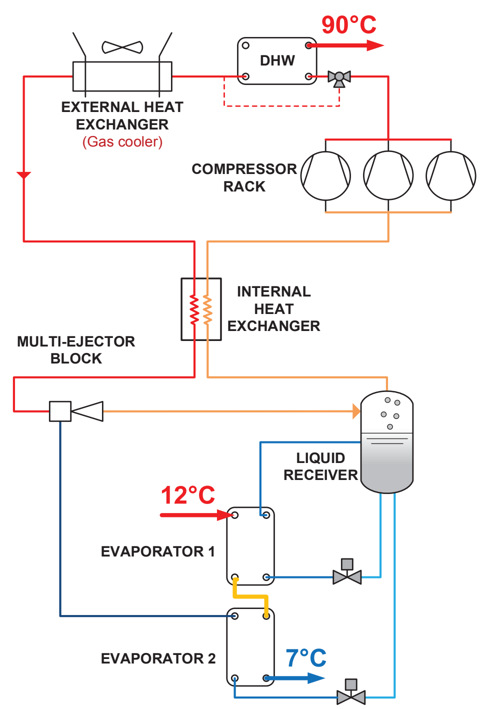


Figure 3: Basic CO_2 circuit drawn by Gustav Lorentzen (left, 1988). Right: State of the art CO_2 Chiller unit, developed within the MultiPACK project.

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The CO_2 chiller shown in Figure 3 represents an innovative approach to adapt water chillers to the properties of CO_2. The evaporators in combination with the Multi Ejectors allow an elevated suction pressure of the compressors, as in the system described in Figure 1, where the compressor is unloaded by the work recovery in the ejector. In Figure 3 the first sections is connected to the liquid receiver 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 process water. The second evaporator is enabled provided more cooling capacity is required, since it is able to further reduce the temperature of the process water to 7 °C. The suction pressure is at this second evaporator 38 bar ($t_o \approx +3$ °C), due to the usage of the Multi Ejectors, which are able to suck all the vapour out of the second evaporator and supply it back to the liquid receiver where the compressors maintain the pressure level.

The CO_2 chiller unit is a compact and energy efficient alternative to traditional chillers applying non-natural working fluids. With the shown configuration, even the requirements of the EU ecodesign directive for Chillers can be satisfied, i.e. such units applying a non-flammable and natural refrigerant can be produced and placed in the market without any restrictions.

2.1. Supermarket HVAC&R:

Commercial refrigeration systems with integrated AC are becoming a trend due to reduced maintenance cost and the trust of end-users to apply natural working fluids all over the supermarket building (Hafner 2014 & 2016; Girotto, 2016). Figure 4 shows the development of such an integrated MultiPACK unit, able to provide all the required cooling for the products inside the supermarket. The unit is equipped with a Multi Ejector and parallel compressors. In addition, the MultiPACK unit supplies heating and cooling to several indoor air handling units (IAHU). In case of heating demand inside the building, hot gas is supplied directly towards the IAHU's. The individually flow rates are controlled locally by feeding valve, located upstream of each IAHU. The cooled refrigerant enters the high side pressure part of the Multi Ejectors. If the building requests cooling, liquid CO_2 is supplied towards the IAHU's. The entire vapour of all IAHU's is sucked by the AC-Ejectors, discharging it towards the separator. The parallel / AC compressors maintain the pressure level of the separator, i.e. providing the cooling capacity for the building.

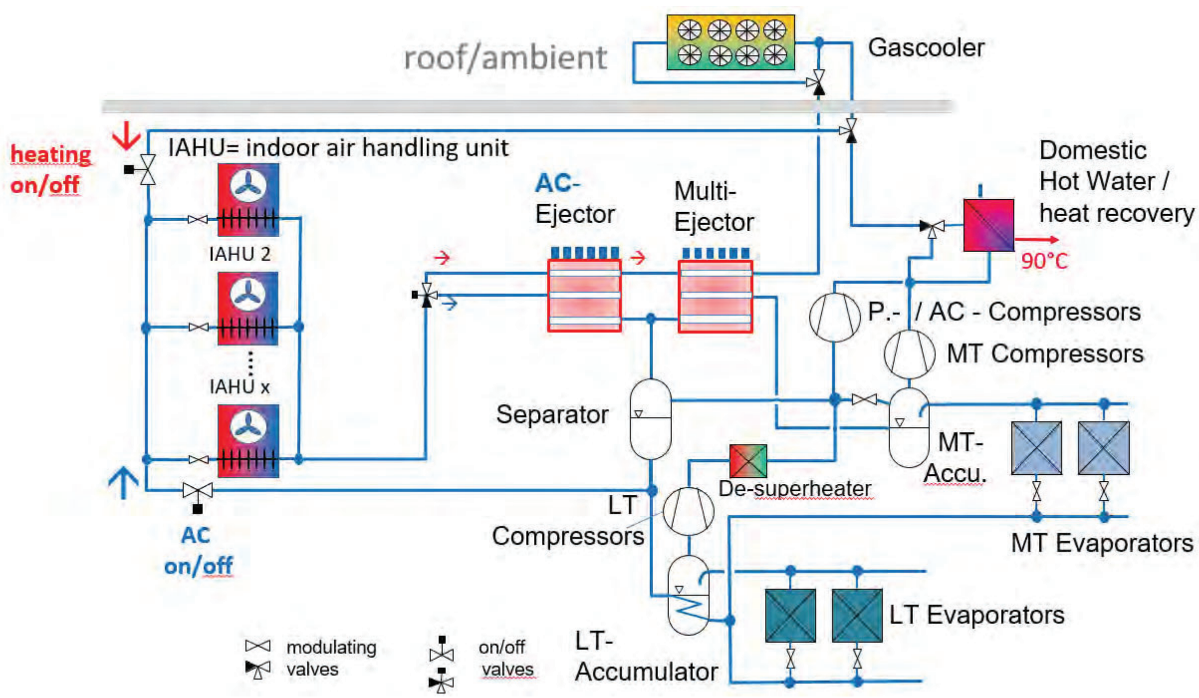


Figure 4: MultiPACK unit design with several individual indoor air handling units.

In many cases, when existing building infrastructure has to be taken into consideration during a refurbishment of a supermarket, AC needs to be integrated through a chilled water loop. Figure 5 shows the development of such an integrated MultiPACK unit with a standard Multi Ejector and parallel compressors. Besides providing all the required cooling capacities for cabinets for chilled and frozen products inside the supermarket, the unit is equipped with the innovative chiller described above (Figure 3, right) and a heat pump part. The two AC evaporators are connected to the separator and AC ejector respectively. The pressure level inside the separator can be adjusted to adapt the cooling capacity provided towards the building by the chilled water loop. In case of additional heating demand during the cold season, an outdoor heat exchanger is able to supply external heat via the second ejector, in this case acting as the Heat Pump (HP) ejector.

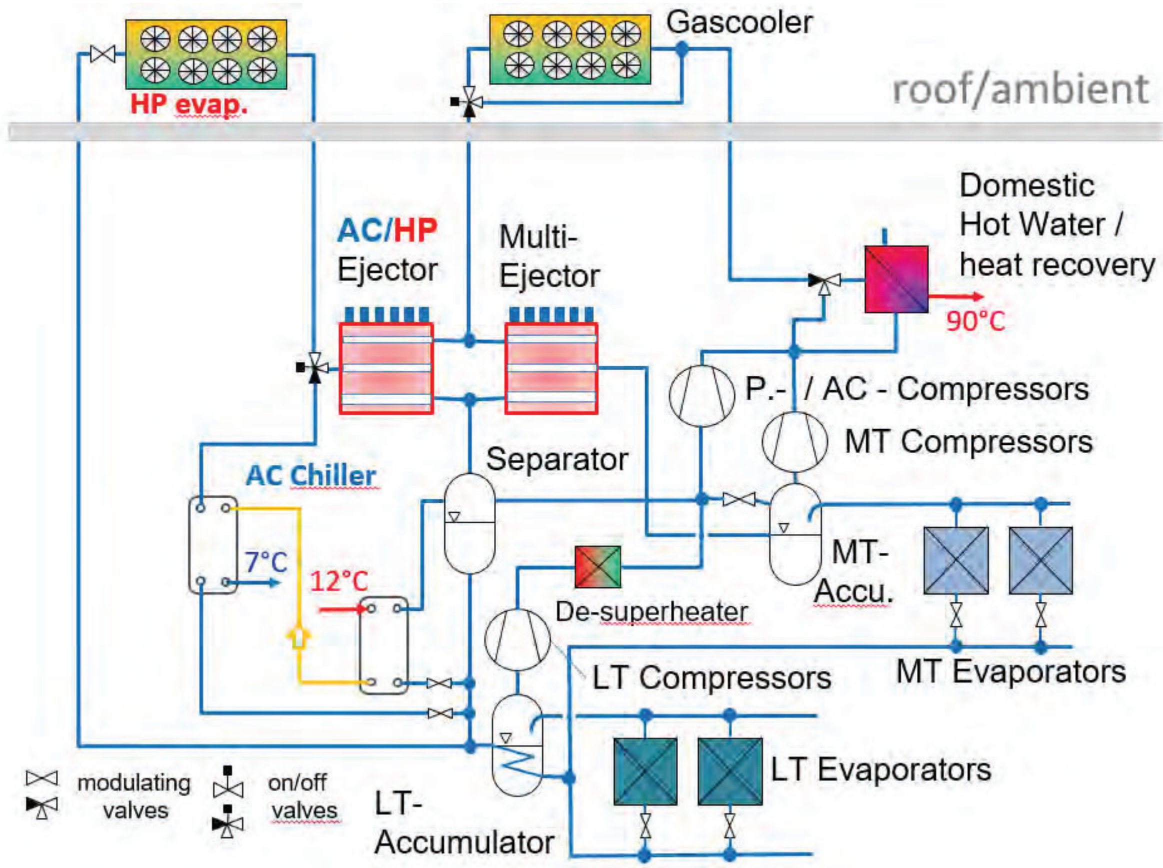


Figure 5: MultiPACK unit design with integrated AC chiller device and heat pump function.

3. INNOVATIONS UNDER DEVELOPMENT

Current developments and research address the three main concerns of supermarket owners regarding all-CO_2 commercial refrigeration systems: cost, efficiency and complexity of the refrigeration loop. Even though CO_2 components and systems are still more costly in some regions than systems with other refrigerants, due to the F-gas regulation and more potential manufacturers competing within the CO_2 sector, the cost difference is decreasing rapidly. CO_2 systems are currently competitive or better than traditional systems in terms of energy efficiency; however, in some cases this improved performance has been achieved with complicated layouts. Therefore, the tendency should be to reduce this complexity without compromising on the energy efficiency, which in turn will have a positive effect on the cost of units.

3.1. Parallel operation of ejectors devoted to different applications

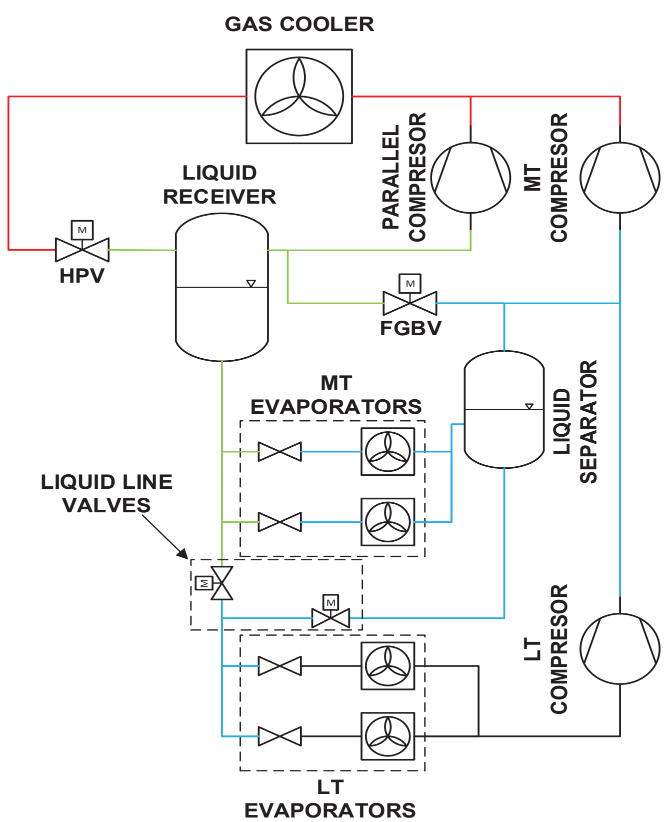
As shown in the previous section, ejectors are applied in CO_2 booster systems in order to lift the pressure of liquid and / or vapour from the separator downstream of the MT evaporators to the liquid receiver (high pressure lift ejectors), and to entrain the refrigerant from the AC evaporator in ejector supported configurations (low pressure lift ejectors). If both solutions are installed in parallel in the refrigeration system, the so-called

AC (low pressure lift) ejector and parallel compressors are in charge of adjusting the conditions of the refrigerant at the AC evaporator as a function of the AC demand. Simultaneously, the high pressure lift ejector is applied to regulate the high pressure level in the system, following the set point indicated by the controller and substituting the previously applied high pressure control valve.
Both ejectors share the same high pressure stream (motive flow). The control of the high pressure could be challenging due to the common use of this mass flow and this situation has been observed in system simulations under the following circumstances:

- when the share of AC load to the total refrigeration load of the installation was relatively high
- if the AC ejector performed inefficiently

A control strategy to deal with such situation has been proposed by Pardiñas (2018) based on detailed numerical simulations, however, it should be verified by field-tests. It consists on adjusting the AC evaporation pressure and pressure lift of the AC ejector to the ambient conditions, since its efficiency is very much dependent on pressure and temperature at the motive nozzle. If the high pressure control is still impossible, i.e. the set-point cannot be reached, the liquid receiver pressure level set-point should be reduced in order to lower the pressure lift requirement at the AC ejector (at a given AC evaporation temperature). This increases the entrainment ratio and reduces the flow requested at the motive nozzle, bringing the control of the high pressure level back to the high pressure lift ejector.

3.2. Control of liquid level at liquid separator to supply LT evaporators



The solution developed by EPTA (2018), shown in Figure 6, to handle the liquid separator level with flooded MT evaporators simplifies very much the layout of efficient CO_2 booster systems for commercial applications. However, there is still space for innovation in this solution, since the stability of the LT evaporators could be compromised when the supply to the expansion valves changes from the liquid receiver to the separator.

A possible improvement of this is to enable an active control of the liquid level of the separator, so that the valve supplying the LT evaporators from the liquid receivers could be removed, i.e. there would be two independent liquid lines, one for the MT evaporators connected to the liquid receiver and a separate one, connected to the liquid separator, for supply of liquid to the LT evaporators. The technical solution is still under development; however, it is based on the implementation of several liquid switches arranged vertically at the liquid separator, and a controller that would shift the opening degree of the MT evaporator (electronic) expansion valves as a function of this liquid level.

Figure 6: Liquid level control in liquid separators of CO_2 commercial refrigeration systems with liquid line valves to supply LT evaporators.

3.3. Low pressure lift ejectors to supply specific cabinets

Commercial refrigeration systems operate usually with two levels of evaporation temperature, MT and LT for cooling and freezing of products, respectively. The targeted evaporation temperature (saturation pressures) for a high efficient CO_2 refrigeration unit are -25 °C (16.9 bar) for LT and -2 °C (33 bar) for MT cabinets. However, the air temperature requested by the different display cabinets of the same compressor suction group

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could be quite different. Conventional systems select a set-point for the evaporation temperature that fits the most demanding cabinet, i.e. the display cabinet that contains products with very low preservation temperature or the most loaded one, due to the amount of product or due to open configuration (high air infiltration). Thus, most of the other cabinets in the same suction group will operate with a lower evaporation temperature than they actually need, which has a negative impact on the performance and energy demand of the entire refrigeration system.

A solution to keep the evaporation temperature at the target value, without compromising the preservation in those specific cabinets, is to implement a low pressure lift ejector as shown on the left part of Figure 7. This solution enables an additional evaporation temperature at a temperature level that is up to 4 K lower within the same compressor suction group. In the sketch, the liquid refrigerant supply for the expansion valve of the ejector supported display cabinet comes from the liquid receiver. However, it could be supplied also from the liquid separator, analogously to the traditional solutions. This would reduce the need for liquid ejector to control the liquid level at the separator.

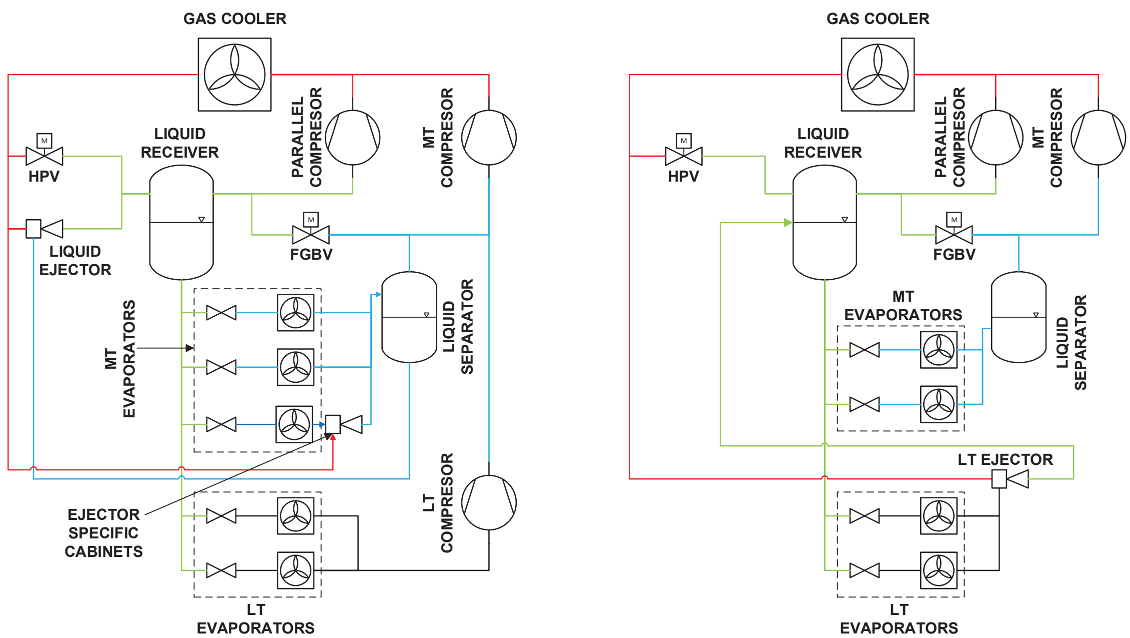

Figure 7: Left, low-pressure lift ejector to supply specific cabinets running at lower evaporation temperature Right, high pressure lift ejector to remove LT compressors in systems with low share of LT load to total load of the supermarket.

3.4. LT evaporation with high pressure lift ejector

It is usual in supermarkets in Europe that the share of the LT load compared to the total load is low. The MT and LT loads in a typical food retail application could account for 120 kW and 25 kW, respectively. The LT load share could be even lower in CO_2 booster systems, when the supermarket chain applies mainly plugin units, with hydrocarbon (R290) as working fluid, for the LT part of the display cabinets and just connect a few LT evaporators to the centralised CO_2 system. Nevertheless, in this case significant investments must be made to cover this reduced LT demand, including dedicated compressors, inverter, de-superheater, etc.

The strategy behind this innovation to eliminate the LT compressors and their auxiliaries is to substitute them by a high pressure lift ejector, as shown in Figure 7 on the right side part. The ejector applies the high pressure stream at the motive nozzle to entrain the flow coming from the LT cabinets and discharge it at the liquid separator pressure level. Since ejectors can handle liquid-vapour mixtures at their suction, implementing overfeed LT evaporation can be done with this innovation, avoiding any additional LT suction accumulator. Finally, due to the stability that usually LT loads have throughout the day and the year, applying fixed size ejectors with simple control is possible. This solution allows also implementing the liquid supply strategy to the LT cabinets from the liquid separator.

4. SUMMARY & CONCLUSIONS

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. Some of these innovations are described in this work.

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 like chilling of process water or direct evaporation for AC purpose into the centralised refrigeration unit is a key success factor for these sustainable vapour compression systems replacing HCFC and HFC systems globally.

The designers and 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. The described innovations will further simplify CO_2 systems in the near future.

Training and knowledge transfer is the key for a successful and fast phase in of CO_2 refrigeration units globally. Therefore, also World Bank and multi-lateral funds should support global education, training and certification as well as covering additional first costs with affordable loans (no interest rate), so the end-users can return the loan during the operational phase, since the new energy efficient system gives them a significant energy / cost saving.

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REFERENCES

1. Banasiak, K.; Hafner, A., Kriezi, E.E.; Madsen, K.B.; Birkelund, M.; Fredslund, K.; Olsson, R. (2015), Development and performance mapping of a multi-ejector expansion work recovery pack for R744 vapour compression units, International Journal of Refrigeration, Volume 57, 1 September 2015, pp. 265-276
2. Elbel, S., Hrnjak P., 2008, Experimental validation of a prototype ejector designed to reduce throttling losses encountered in the transcritical R744 system operation. Int. Journal of Refrigeration, vol 31, page 411-422. doi:10.1016/j.ijrefrig.2007.07.013
3. Elbel, S. 2011, Historical and present developments of ejector refrigeration systems with emphasis on transcritical carbon dioxide air-conditioning applications. Int. Journal of Refrigeration, vol 34, page 1545-1561. doi:10.1016/j.ijrefrig.2010.11.011
4. EPTA, 2018, https://www.eptarefrigeration.com/en/node/739
5. Girotto, S., 2016. Direct space heating and cooling with refrigerant CO_2. ATMOsphere Europe, Barcelona. http://www.atmo.org/media.presentation.php?id=754.
6. Hafner, A., Claussen, I.C., Schmidt, F., Olsson, R., Fredslund, K., Eriksen, P.A., Madsen, K.B., 2014, Efficient and integrated energy systems for supermarkets. Proceedings of the 11th IIR Gustav Lorentzen Conference on Natural Refrigerants, Hangzhou, China.
7. Hafner, A., Banasiak, K., 2016: Full scale Supermarket Laboratory R744 Ejector supported & AC integrated parallel compression unit. Proceedings of the 12th IIR Gustav Lorentzen Natural Working Fluids Conference, Edinburgh, Scotland.
8. Lorentzen, G., Pettersen, J., 1992. New possibilities for non-CFC refrigeration. IIR Int. Symp. on Refrigeration, Energy and Environment, Trondheim, Norway, June 22-24, pp.147-163.
9. Pardiñas, Á.Á., Hafner, A., Banasiak, K., Kvalsvik, K.H., Larsen, L., 2018, Strategy for the control of two groups of ejectors operating in parallel in integrated R744 refrigeration systems. Refrigeration Science and Technology, 2018-June, pp. 1069-1076.