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Attaining a higher flexibility degree in CO_2 compressor racks

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ABSTRACT

CO_2 compressor racks have shown their suitability for commercial and industrial refrigeration systems at any location and climate. Even if some references state that CO_2 units can compete in capital cost with any other alternative solution, often investment costs are still the main barrier for the global expansion of CO_2.

This work explores, numerically and experimentally, the implementation of "pivoting" compressors, i.e. compressors that can operate in the medium temperature (MT) and parallel compressor suction groups, depending on ambient conditions, cooling loads and use of ejector. The objective is to increase the flexibility of CO_2 compressor racks, keeping the efficiency and, potentially, reducing the investment. This study shows that this solution with "pivoting" compressors is beneficial in ejector-supported systems, since the investment cost of the ejectors is compensated by a lower number of installed compressors, as compressor capacities can be applied in more flexible ways.

Keywords: Refrigeration, Carbon Dioxide, Compressors, Switching, Pivoting.

1. INTRODUCTION

CO_2 (R744) is currently the refrigerant choice for commercial refrigeration in many areas of the World, particularly Europe and Japan, and is entering other applications such as industrial refrigeration, small stores or ice rinks (Zolcer Skačanová and Battesti, 2019). Gullo et al. (2018) pointed out that the technological developments implemented nowadays in R744 supermarket-refrigeration systems allow that they outperform HFC-based units under almost any climate conditions. These technological developments comprise, for example, mechanical subcooling, overfed evaporators (with or without liquid ejectors) or vapour ejectors for different purposes such as transferring load to parallel compressor or supporting efficient AC integration. However, they elevate the level of complexity and investment cost, hindering their implementation.

Vapour ejectors to transfer the load from the medium-temperature (MT) compressors to the parallel compressor suction group contribute to reducing the energy consumption of refrigeration systems. Ejectors entail a significant initial cost, and potentially additional parallel-compressor capacity only used when the ambient temperature (gas cooler outlet temperature) is high. This article explores the implementation of "pivoting" compressors, i.e. compressors that can alternate between the MT- and parallel-compressor sections depending on the operating conditions, to reduce the installed compressor capacity in ejector-supported CO_2 refrigeration systems without any negative impact on the capacity delivered. Such technology was already discussed in Pardiñas et al. (2018a) to increase the flexibility of compressors packs and optimize energy efficiency by choosing the right configuration of active compressors per section, but that study disregarded the potential to reduce the number of compressors installed. The solution proposed is described and compared with the state-of-the-art system. A numerical model was used to evaluate this "pivoting" compressor solution, and the study was complemented with experimental data. The results are discussed in this paper looking into compressor-capacity installed (and unused), energy efficiency and a simplified cost analysis.

2. CO_2 COMPRESSOR RACK WITH PIVOTING COMPRESSORS

Figure 1 shows a CO_2 compressor rack for supermarket refrigeration at two temperature levels, medium-temperature (MT) and low-temperature (LT), with parallel compression and vapour ejectors. The main modification suggested in this study is the installation of a set of two valves upstream of compressors, which become the "pivoting" compressors. In the configuration represented in Figure 1, there would one dedicated MT compressor, one parallel compressor, while the other two compressors are "pivoting" compressors.

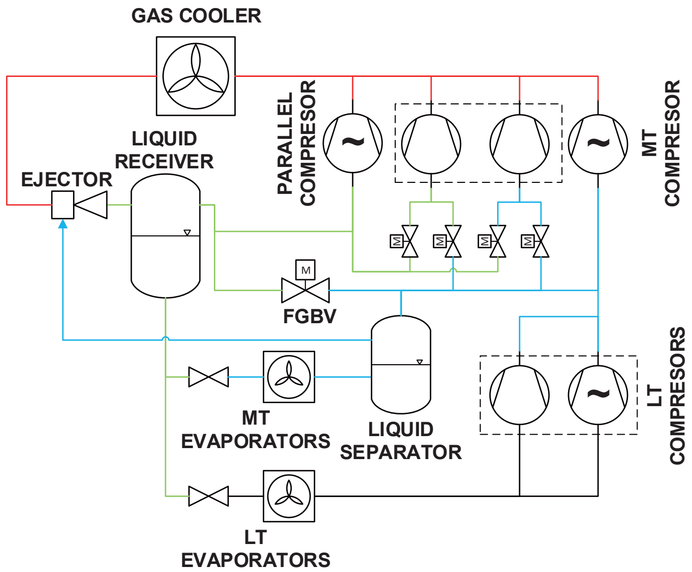

Figure 1. CO_2 compressor rack with "pivoting" compressors.

"Pivoting" compressors can alternate between the MT and parallel compressor suction groups depending on the capacity requirements by activating the corresponding valve. The aim is that the compressor-capacity (number of compressors) installed in the rack can be reduced without any effect on the delivered cooling or efficiency, using compressors during longer periods of the year exactly for the purpose that they are needed at each time. This is particularly important in ejector-supported systems, as a larger parallel-compressor capacity is needed when the vapour ejector is able to unload the MT compressors. On the other hand, parallel compressors would be idle during the cold part of the year, when mostly MT compressors are needed, i.e. compressor capacity ends up unused and occupying valuable space. The implementation of "pivoting" compressors involves that they could be used as parallel compressors when the ejectors are entraining a relatively large mass flow rate from the MT section to the parallel-compressor suction group; else these compressors are connected to the MT suction group.

3. METHODOLOGIES

3.1. EXPERIMENTAL SETUP

SuperSmart-Rack is the experimental setup available at Varmeteknisk laboratory at NTNU (Trondheim, Norway) that was utilized to analyze the benefit of implementing the "pivoting" compressor concept to CO_2 compressor racks. A detailed description can be found in Pardiñas et al. (2018b) and cannot be included here for space reasons. The setup consists of a versatile CO_2 refrigeration system, which allows testing very different system configurations (booster, ejector supported, air conditioning integration, etc.), and several auxiliary circuits to emulate the demands and operating conditions in a supermarket.

The unit comprises eight semi-hermetic reciprocating compressors manufactured by Bitzer, with the characteristics shown in Table 1 and arranged as in Figure 2: two LT compressors, one MT compressor, one parallel (or IT) compressor, and four "pivoting" compressors (default operating mode indicated also in the table). The ejector installed is a Multi Ejector HP 1875 LE 400 CTM 6 from Danfoss (https://assets.danfoss.com/documents/DOC300732394440/DOC300732394440.pdf), and the system has a high-pressure valve (HPV) in parallel to allow direct comparison between ejector-supported and HPV configurations. Up to seven helical coaxial tube-in-tube heat exchangers can be operated as evaporators, using a glycol solution as heat source. Five of them are MT evaporators and can provide more than 60 kW load, and the other two are LT evaporators and provide between 15 kW and 20 kW. AC evaporators and ejectors are not considered in the present study. Up to three brazed plate heat exchangers can be used as gas coolers, using three different loops at different temperature as heat sinks.

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3.2. SIMULATION MODEL

Prior to any experimental campaign, the research question of this article was investigated numerically to minimize the number of tests needed by pre-selecting potential combinations of compressors. The simplified and steady-state numerical model emulated SuperSmart-Rack experimental setup and was programed in EES (Engineering Equation Solver http://www.fchartsoftware.com/ees/). Compressors from Table 1 were modelled using the polynomials available in the software of the manufacturer (https://www.bitzer.de/websoftware/), and accounting for the effect of density (if actual superheating different to reference conditions) and of frequency with VSD compressors. Concerning the ejector, fixed efficiency was used, defined as in the work by Elbel and Hrnjak (2008), e.g. equal to 30% @35 °C gas cooler outlet temperature. The remaining components were modelled neglecting heat losses and pressure drops.

Table 1. Characteristics of the compressors in SuperSmart-Rack. VSD stands for variable speed drive.

Compressor No. (Model)	Operating mode (default mode)	Displacement [m^3/h] @ 50 Hz	VSD? (frequency range)
1 (2GME-4K)	LT	5	No
2 (2JME-3K)	LT	3.5	Yes (30 – 70 Hz)
3 (4MTC-10K-40S)	MT	6.5	Yes (30 – 80 Hz)
4 (4MTC-10K-40S)	Pivoting (MT)	6.5	No
5 (4JTC-15K-40P)	Pivoting (MT)	9.2	No
6 (2KTE-7K-40S)	IT	4.8	Yes (30 – 80 Hz)
7 (2KTE-7K-40S)	Pivoting (IT)	4.8	No
8 (4JTC-15K-40P)	Pivoting (IT)	9.2	No

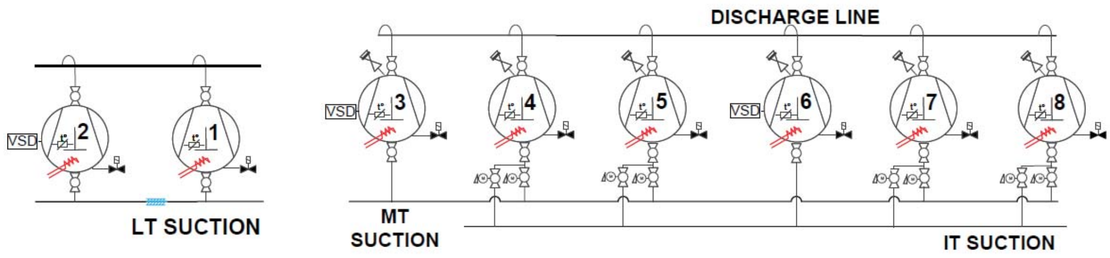

Figure 2. Compressor arrangement in the experimental setup SuperSmart-Rack, made by Advansor. The largest numbers in the centre of the compressor symbol correspond to the reference number in Table 1.

3.3. CONDITIONS AND CONFIGURATIONS INVESTIGATED

CO_2 compressor racks are sized at the design conditions, considering the maximum loads (constant throughout the year) and harsh (high) ambient temperature. It is in these conditions that the compressor-capacity is defined and that the potential to reduce the number of compressors installed by "pivoting" should be evaluated. In our case, the design conditions listed below were those considered for the actual sizing of the SuperSmart-Rack facility, which aimed at the typical refrigeration loads for medium-sized supermarkets in Norway.

- Gas cooler outlet temperature 35 °C, with high pressure setpoint 89 bar(a). Simulations and tests were also performed at gas cooler outlet temperatures ranging from 10 °C to 35 °C to evaluate if the selected compressor rack would meet the refrigeration loads also at these conditions, but these results are not shown in this paper due to space constraints.
- Receiver pressure 36 bar(a).
- MT load 60 kW, at evaporation temperature -8 °C (approximate pressure 28 bar(a)).
- LT load 15 kW, at evaporation temperature -30 °C (approximate pressure14.3 bar(a)). Both LT compressors (see Table 1) are always in operation to meet the specified load, and thus this will not be discussed further in the RESULTS section.
- Regulation of evaporators' expansion valves, at MT and LT levels, to achieve 8 K superheating degree. This setting differs from the flooded operation recommended with CO_2 evaporators, but is still common practice in an important part of the compressor racks installed worldwide.

Concerning the configurations investigated, the booster system with parallel compression and HPV was taken as base, and the ejector-supported booster system with parallel compression as alternative. In both cases, the effect of "pivoting" compression was investigated.

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4. RESULTS

4.1. Parallel compression system with HPV

Figure 3 shows the effect that "pivoting" compressors would have on a booster system with parallel compression and HPV, by representing how compressors need to be distributed in the different groups if the system has "pivoting" compressors (right) or not (left), and which would be the unused capacity in each case at the design conditions. Compressor numbering corresponds to that defined in section 3.1 (Table 1). It should be specified here that the configuration without the "pivoting" feature has compressors 4, 5, 7 and 8 arranged as shown in Table 1 under "default mode" (in parenthesis).

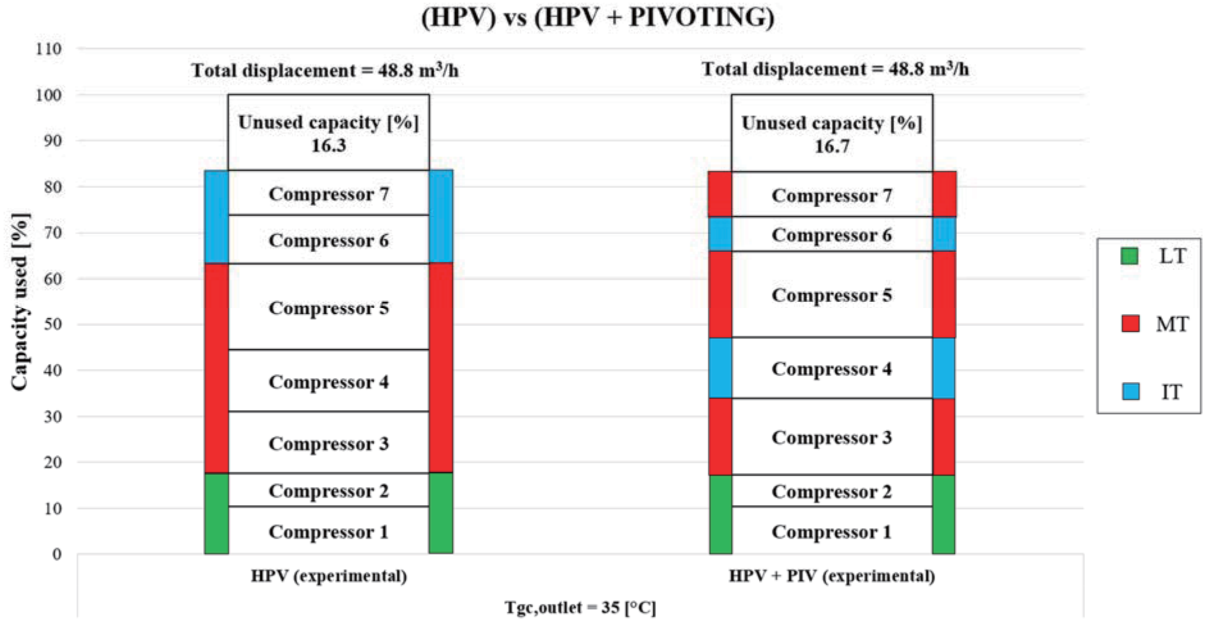

Figure 3. Effect of implementing "pivoting" compressors on the compressor-capacity used by a booster system with parallel compression and HPV (without ejector) at design conditions as defined in section 3.3.

As can be seen in Figure 3, implementing "pivoting" compressors has negligible effects on this configuration of CO_2 compressor rack. Three MT compressors and two parallel (IT) compressors are needed at this point, independently of the use of "pivoting" or not, and the only difference resides on how the compressors could be arranged between the MT- and parallel-compressor groups. The unused capacity at the design point would be in the range of 16% and 17%, adding up the remaining capacity of the VSD compressors (2, 3 and 5). Under any other conditions, it would be enough with these compressors to meet the load requirements, and thus compressor 8 would be unnecessary under this configuration. It must be also pointed out that "pivoting" has a negligible effect on the performance of the compressor rack. For this comparison, COP was defined in a very simple way as the ratio of the total refrigeration load produced by the system, summing up refrigeration at LT and MT levels, to the total power consumption of the compressors in the rack. The COP values retrieved from the experimental campaign were equal to 1.75 and 1.76 without and with "pivoting" compressors, respectively.

4.2. Ejector-supported parallel compression system

The same exercise was performed in Figure 4 with the ejector-supported CO_2 compressor rack. The traditional configuration without "pivoting" compressors (left) has much higher unused capacity at the design point than the corresponding unit without ejector, being these values equal to 33.2% and 16.3%, respectively (or 19.2 m^3/h and 7.8 m^3/h, respectively). The origin of all this unused capacity in the ejector-supported configuration without "pivoting" could be unclear looking only at the active compressors at the design point. The explanation is that, due to the good performance of the ejector at 35 °C gas cooler outlet temperature, MT compressors are heavily unloaded in favour of parallel (IT) compressors. The two parallel compressors from the system without ejector, compressors 6 and 7, are insufficient to meet the capacity requirements at those conditions, and a larger parallel compressor is in operation (compressor 8). However, as soon as the unit is operating below full load or with heat rejection at lower temperatures, the combination of compressors 6 and

http://dx.doi.org/10.18462/iir.gl.2020.1123

8 becomes too high, and compressor 7 would be needed to close the capacity gap between compressor 6 only (at highest frequency) and compressors 6 (at lowest frequency) and 8. An analogous effect is observed with the MT compressors, and thus compressor 4 needs to be installed even if it is not in operation at the design point. In conclusion, the ejector implementation involves higher shifts of the capacity from the MT to the parallel section and vice versa under changing operating conditions, than a system with HPV.

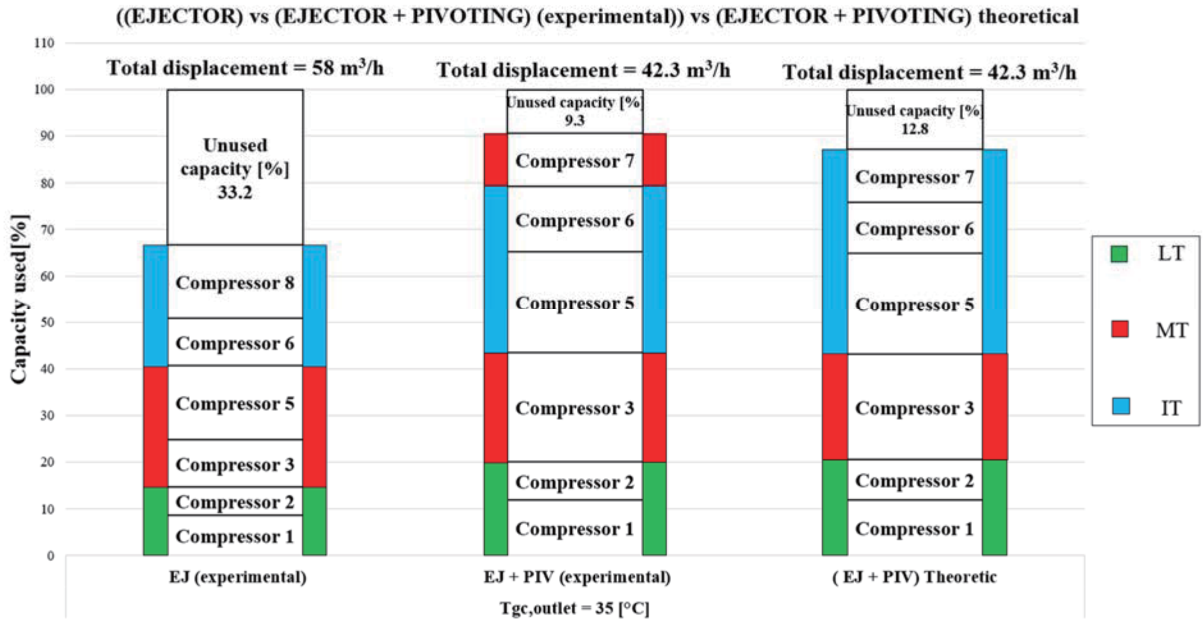

Figure 4. Effect of implementing "pivoting" compressors on the compressor-capacity used by an ejector-supported booster system with parallel compression at design conditions as defined in section 3.3.

Figure 4 indicates also how the implementation of "pivoting" compressors affects the ejector-supported CO_2 compressor rack, reducing importantly the unused and installed compressor-capacity compared to the case without "pivoting" compressors. The reason is that the large shifts of capacity between the compressor suction groups (MT and parallel) caused by the introduction of ejector can be covered with fewer compressors, if these units are flexibly operated where they are needed. As indicated in Table 1 and Figure 2, compressor 3 and 6 are dedicated to fixed suction groups (MT and parallel compressor, respectively) and are always in operation since they are coupled to the VSD. Two additional "pivoting" compressors (5 and 7) would be enough to cover these changes in the capacity requested at the different temperature levels avoiding capacity gaps. Thus, the system could operate with up to three parallel compressors when the ejector performs best and unloads significantly the MT section, and up to three MT compressors when heat rejection is performed at lower ambient temperatures and the ejector performs basically as a high-pressure control valve.

The reason why there are two "pivoting" cases in Figure 4 at the same design conditions is that one comes from the experimental campaign (middle column) and the other from the numerical analysis (right column). According to the simulations, only one MT compressor operating at maximum capacity would suffice due to the ejector support, leading to three parallel (IT) compressors. However, the experimental campaign showed that the share should be two MT compressors and two IT compressors instead. Here lies the main disagreement between the experimental and numerical results, which otherwise was very positive given the relative simplicity of the numerical model. The reason behind this mismatch is that the numerical model underestimates the performance of the internal heat exchanger located downstream of the gas cooler and used to superheat the suction stream to the parallel compressors. Thus, the temperature of the ejector motive flow was lower in the tests, leading to slightly lower ejector performance and entrainment ratio. In any case, the installed compressor-capacity would be identical, and the difference in unused capacity low (approximately 1.5 m^3/h).

The COPs of the CO_2 compressor racks with and without ejector at the design point, calculated with the experimental data, were 1.88 and 1.75, respectively (around 7.5% higher with the ejector-supported unit). A negligible COP difference was observed between the ejector-supported system with and without "pivoting".

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4.3. Cost analysis

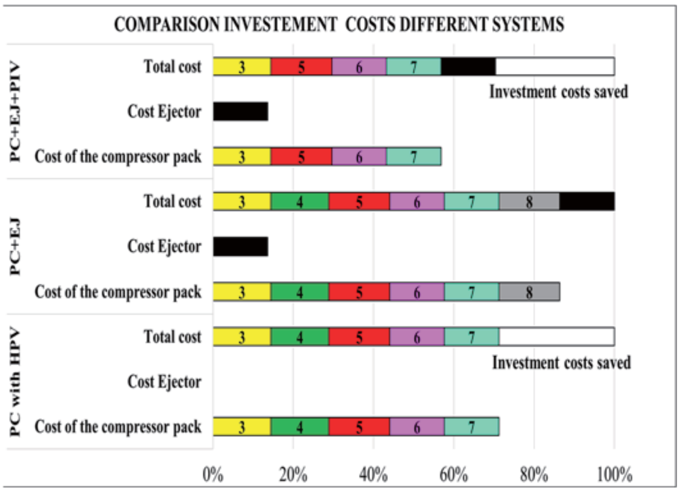

Figure 5. Simplified cost analysis. PC = parallel compressor, EJ = ejector, PIV = pivoting.

A simplified cost analysis was done to compare the different configurations with and without "pivoting" compressors. Only the costs of the compressors and, eventually, Multi Ejector were considered. It was assumed that compressor cost is almost independent of the compressor capacity (in the range used in SuperSmart-Rack) and that the Multi Ejector costs approximately the same as a compressor. Other components in the compressor rack were not accounted for in this analysis since they are almost identical independently of the configuration. The cost of the set of valves to turn a compressor into "pivoting" was also neglected. It can be seen in Figure 5 that the highest investment cost would come from the ejector-supported unit without "pivoting" solution. This could hinder the implementation of ejector technology, even when it leads to a reduction in the power demand. On the other hand, at equal cooling capacities, the use of "pivoting" compressors with ejector reduces the number of installed compressors and compensates the increase of cost due to the Multi Ejector, having a comparable investment to the HPV unit.

5. CONCLUSIONS

This paper investigated if the implementation in a CO_2 compressor rack of "pivoting" compressors, i.e. compressors that can operate as MT or parallel compressors depending on ambient conditions, cooling loads and ejector performance, has a positive impact on the flexibility of the system and could reduce the installed compressor-capacity and thus the investment cost. The main conclusion from this study is that "pivoting" is mostly beneficial if the system is ejector-supported, since it is possible to keep the efficiency improvement due to the vapour ejector that unloads the MT compressors in favour of the parallel compressors, and reduce at the same time the total number of compressors installed. In the investigated configuration, a typical case for a medium size supermarket, two compressors could be removed. All in all, ejector-supported CO_2 compressor racks with "pivoting" compressors could be at the same level of investment cost as relatively simpler configurations. Test of layouts with integrated AC load as well as development of a dedicated control system (hardware & software) will be the next steps of the joint development within the teams.

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