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Performance improvements of supermarket R744 systems by pivoting compressor arrangements

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ABSTRACT

The adoption of the EU F-Gas regulation 517/2014 and the development of the Multi Ejector concept have led CO_2 to take center stage as one of the preferred solutions in several applications, at the expense of synthetic refrigerants. Despite the expected significant energy saving in warm climates using the Multi Ejector, the increase in investment costs and level of complexity would hinder its spread.

In this work a numerical and experimental campaign have been performed to explore the implementation of "pivoting" compressors, i.e. a technique that enables the medium temperature (MT) and parallel (IT) compressors in a booster system to be interchangeable according to cooling loads, ambient conditions and ejector capacity. The novel configuration presented in this work helps to downsize the installed compressor capacity in ejector-supported systems while maintaining all the benefits due to the ejector. The basic version of the solution is based on: i) MT and low temperature (LT) compressors, ii) high pressure controlled through a Multi Ejector both during summer and winter conditions. The tests performed in the laboratory proved how the "pivoting" solution is beneficial to attain a higher degree of flexibility with more compact systems while maintaining the efficiency and justifying economically the ejector implementation. An additional solution called LT "pivoting", i.e. connecting LT compressors either to MT or IT compressors, proved to be particularly useful for energy saving.

Keywords: Refrigeration, Carbon Dioxide, Ejector, Pivoting.

1. INTRODUCTION

Carbon dioxide (R744) has entered into the market in many different applications such as commercial and industrial refrigeration, small stores and applications on-board. The tremendous improvements over the years allowed R744 systems to outperform HFC-based units, replacing their use with a more environmentally friendly and energy efficient solution and according to the EU F-Gas Regulation 517/2014(European Commission 2014). The technological developments comprise mechanical subcooling, overfeed evaporators and ejectors to transfer the load to parallel compressors favouring a lower energy consumption (Gullo, Hafner et al. 2019). However, the energy consumption reduction achievable in warm climates through the ejectors is counterbalanced by the higher level of system complexity and investment costs, hindering their implementation. Moreover, the highly variating compressor capacity requirement between medium temperature (MT) and parallel (IT) compressors during warmer or colder ambient conditions, would entail uneven use of the compressor capacity installed (Expósito-Carrillo, Sánchez-de La Flor et al. 2021).

This work explores numerically and experimentally the use of the "pivoting" arrangement in a R744 booster systems for a medium-sized supermarket. This technology has been already object of discussion in (Hafner 2017, Pardiñas, Hafner et al. 2018) with the aim of increasing the flexibility of compressor packs by choosing the right combination of compressors, depending on cooling needs and ambient conditions. The layout

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proposed is compared with the state-of-the-art system to investigate its potential to reduce investment costs (CAPEX) and system footprint, hoping for no negative impact on the energy performance (OPEX). The pivoting concept has also been extended to the low-temperature (LT) compressors, with the goal of extending the operational hours of the parallel compressors during the cold season. The results are discussed in terms of compressor-capacity used compared to installed and energy efficiency.

2. R744 BOOSTER SYSTEM WITH PIVOTING COMPRESSORS

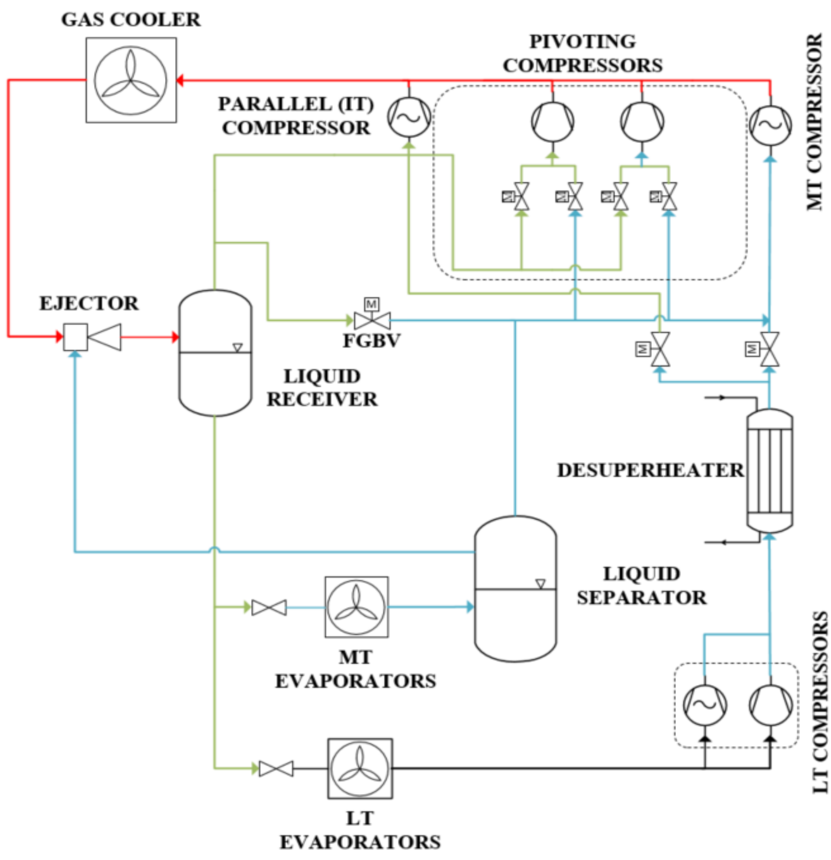

Figure 1: R744 compressor rack with Pivoting compressors.

Figure 1 illustrates a typical layout of a R744 booster system for a medium-sized supermarket which supplies provision cooling (medium-temperature, MT) and freezing (low-temperature, LT). The system belongs to the 3rd generation of CO_2 refrigeration systems, where parallel compressors and vapor ejectors are implemented (Gullo, Hafner et al. 2018). The main update of the layout represented is the introduction of the "pivoting" compressors, i.e. the installation of two valves upstream of the suction port of some of the compressors. The "pivoting" compressors (MT & IT) do have a common discharge manifold. The "pivoting" arrangement can interchange MT and parallel (IT) compressors among them depending on the capacity requirements, as a function of cooling loads and gas cooler outlet conditions. The LT "pivoting" compressors require the installation of two valves downstream of the discharge port to enable the connection either to the suction of the MT compressors-or liquid receiver. This feature can be particularly useful if one the two sections is not in operation under certain conditions, and the decision to discharge to one of the two suction lines should be taken focusing on efficiency and requested capacity.

The regulation of the high pressure along all the temperature domain examined is dealt only by the ejector. During summer conditions with gas cooler outlet temperatures above 20 °C, the ejector acts as a traditional high-pressure control device while lifting some refrigerant from the MT evaporation pressure to the liquid receiver pressure, according to the pressure lift and motive conditions. For lower gas cooler outlet temperatures, the ejector throttles the high-pressure refrigerant to the pressure of the liquid receiver, acting as a traditional high-pressure valve.

3. METHODOLOGIES

3.1. Experimental system architecture

The experimental setup available at Varmeteknisk NTNU/SINTEF laboratory (Trondheim, Norway) called SuperSmart-Rack was used to analyze the effects of implementing the "pivoting" concept into the 3rd

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generation of R744 refrigeration systems. The system is very flexible and allows to test many different conditions and system layouts such as booster, parallel compression, ejector-supported unit with and without air-conditioning integration. Auxiliary loops are used to emulate the different demands and operating conditions typically experienced in a supermarket.

The refrigeration unit comprises seven helical coaxial tube-in-tube heat exchangers which use glycol solution as heat source. Five of them are MT evaporators and the other two are LT evaporators which can provide more than 60 kW (MT side) and around 15-20 kW (LT side). Eight semi-hermetic reciprocating compressors manufactured by Bitzer are installed in the unit, arranged in the following way: two LT compressors, one MT compressor, one parallel (IT) compressor and four pivoting compressors. The compressor features will be presented in the next subsection. The ejector installed is a Multi Ejector CTM Combi HP 1875 LE 600 from Danfoss (https://assets.danfoss.com/documents/DOC300732394440/DOC300732394440.pdf), in parallel with the HPV as safety device. The gas cooler section consists of three brazed plate heat exchangers which use three different loops (glycol solution, water, CO_2) as heat sinks. Further details can be found in Pardiñas (insert article).

3.2. Compressor packs

The aim of the paper was to investigate firstly numerically and later experimentally the minimization of number of compressors installed via the use of "pivoting" compressors. The compressor polynomials were obtained from the software of the manufacturer (https://www.bitzer.de/websoftware/), and were used to evaluate their performance in terms of mass flow and power consumption, and considering the effect of superheat at the suction port and the rotational speed for VSD compressors. Their features have been summarized in Table 1 and illustrated in Figure 2.

Table 1: Features of the compressors installed in the facility (P: pivoting mode; NP: non-pivoting mode).

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

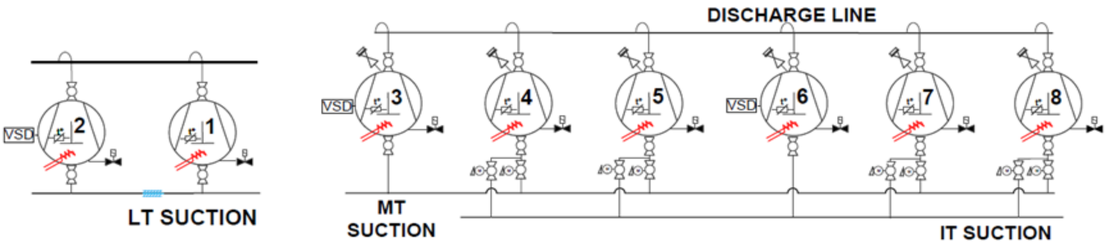

Figure 2: Compressors arrangements in the experimental facility SuperSmart-Rack. The numbers are referred to the different models in the table above.

3.3. Experimental conditions and configurations investigated

The aim of the study presented was also to evaluate the impact of the pivoting arrangement on the cooling load supplied, system efficiency and reliability of a CO_2 Multi Ejector supported refrigeration unit at different

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conditions and with set loads at MT and LT. Data were logged when steady state was achieved at the following operating conditions (Table 2):

Table 2: Tests condition used for the system with and without "pivoting".

Parameter	Range values	Notes
Gas cooler outlet temperature [°C]	10 / 15 / 20 / 25 / 30 / 35	Summer mode for T ≥ 25 °C, Winter mode for T ≤ 20 °C
High pressure [bar]	55 / 55 / 61.4 / 68.9 / 76 / 89	At T_{gc} = 10 °C low pressure level allowable
Receiver pressure [bar]	36	
MT load [kW]	60	4
LT load [kW]	15	
MT / LT evaporating temperature [°C]	-8 / -30	Expansion valve control superheat to 8 [K]
CO_2 Outlet temperature desuperheater [°C]	25	

Two data acquisition systems were synchronized to register the data from the sensors. The first provided by Danfoss had a sampling rate of 5 s. The second was a LabVIEW acquisition system, with a sampling rate of 1 s, in charge of measuring data from active power meters, refrigerant mass flow meters and volumetric flow meters, pressure transducers and temperature sensors. The LabVIEW program was also used to adjust the loads and operating conditions of the refrigeration unit through the control of the different components implemented on the secondary loops (water, glycol and auxiliary CO_2 loop) which comprise pumps, valves and electric heaters. Data from the Danfoss unit was mostly used for control purpose, while measurements from LabVIEW sensors were used for analysis due to their better accuracy. The most important characteristics of the sensors connected to LabVIEW are listed in Table 3:

Table 3: List of the sensors used and their accuracy for data acquisition.

Type	Manufacturer & Sensor's model	Accuracy
Active power meter (compressors)	Schneider Electric A9MEM3150	± 1% of reading
Volumetric flow meter	Endress + Hausser Picomag	±(0.8% of reading + 0.2% of set span)
Temperature sensors	Pt 100 Class B DIN 1/3 on tube	±1/3(0.3 K + 0.005*temp(°C))
Pressure transducers	Endress + Hausser PMP21	± 0.3 % of set span
Differential pressure transducers	Endress + Hausser PMD75	± 0.035 % of set span
Mass flow meters	Rheonik RHM	± 0.21 % of reading

3.4. Simulation tools

The steady-state numerical model used to emulate the SuperSmart-Rack was programmed in EES (Engineering Equation Solver, http://www.fchartsoftware.com/ees/). The mass and energy balances over all

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the cycle were set according to the operating conditions, depending on the status of the Multi Ejector block. The operating conditions where the Multi Ejector was able to deliver vapor from the evaporator pressure level to the receiver pressure level needed to be evaluated carefully because of its impact on distributing the load between the MT and parallel compressors. The gradually unloading of the MT compressors supporting the parallel compressors has clearly a huge impact on choosing the compressor combinations, requiring the use of an additional tool to evaluate the Multi Ejector performance (Coolselector®2 free cooling calculation software | Danfoss). This software is based on data collected during an experimental campaign performed by SINTEF, which consisted of 724 test points, as illustrated in Table 4.

Table 4: Number of points tested for the Multi Ejector HP 1875 400 CTM 6 from Danfoss.

Vapor cartridge	Cartridge 1	Cartridge 2	Cartridge 3	Cartridge 4
Capacity	6 [kW] 125 [kg/h]	12 [kW] 250 [kg/h]	25 [kW] 500 [kg/h]	50 [kW] 1000 [kg/h]
Number of points	463	126	58	77

4. PRELIMINARY EVALUATION OF THE EJECTOR PERFORMANCE

A preliminary analysis of the Multi Ejector block has been carried out considering its impact on sharing the loads between the two pressure levels, which would lately affect the number and types of compressors in operation. A disagreement between test results and CoolSelector had been already observed in (Álvarez Pardiñas, Contiero et al. 2020, Contiero, Hafner et al. 2021) and two reasons have been identified. On the one hand of the pressure drop occurring along the suction line, due to the presence of the mass flow meter and liquid separator. These pressure losses would be more important at higher heat rejection temperature, when the ejector is entraining more refrigerant from the MT pressure level. On the other hand because of the inaccuracy of CoolSelector on predicting the ejector performance, since the different vapor cartridges have been tested individually and later combined numerically. Thus, part of the degradation can reasonably be attributed to the fact that the combined operation of different cartridges might have a mutual impact on the individual cartridges' performance. In order to quantify the impact of each of these two aspects, two different tests have been carried out: the first aiming to give an estimation about the discrepancy between the tests and CoolSelector, including pressure drops and CoolSelector's uncertainty, and the second to measure the impact of CoolSelector's uncertainty with respect to the total deviation indicated in the first tests.

The pressure lift occurring between Multi Ejector ports read by the differential pressure sensor (Figure 3 (left)) becomes significantly different from the difference between the pressures registered by the transducers at receiver and MT evaporation level. This has an impact on the ejector performance (Figure 3 (right)), and the ejector efficiency does not exceed 22% and the entrainment ratio 25 % at the highest gas cooler outlet temperature investigated. The deviation between CoolSelector and the test reaches almost 41%.

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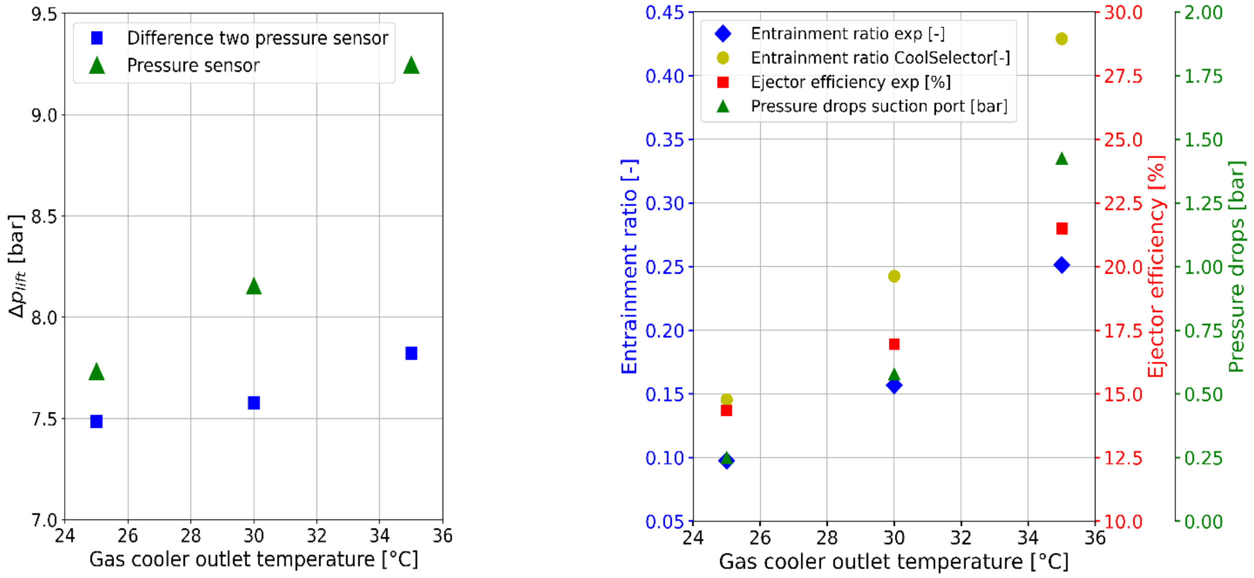

Figure 3: Experimental results in terms of ejector performance for the baseline case (no "pivoting" supported unit).

As second step, considering the real pressure lift and the slight subcooling occurring along the high-pressure line between gas cooler unit – ejector, a second test has been performed (Figure 4). The pressure lift is within an offset of +/- 0.2 respect to the setpoint defined while the entrainment ratio still presents a deviation around 16.97% in this specific case. All in all, even accounting the real pressure lift achieved by the Multi Ejector in the numerical simulation, there is a discrepancy which depends on the motive conditions.

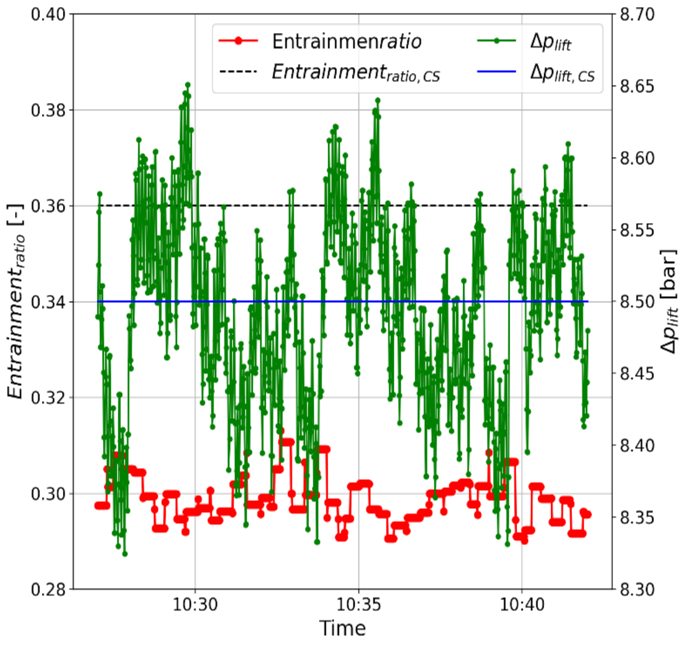

Figure 4: Entrainment ratio and pressure lift in the second stage of tests to quantify the mismatch between CoolSelector and test results.

Figure 5 (left) illustrates how the Multi Ejector alone is able to control satisfactory the high-pressure side. An increment of around half bar has been noticed for both the receiver pressure and the MT evaporating pressure compared with the setpoint (Figure 5(right)). This latter difference is mainly related to the logic behind the compressor's regulation: the compressor pack would keep under control the temperature and thus the pressure at the suction port, while the evaporating temperature would be defined by the pressure drops occurring over the pipes which connect the outlets of the evaporators to the suction ports of the MT compressors. Consequently, if more refrigerant is entrained by the ejector, less refrigerant will flow through the pipes upstream of the compressors and thus the pressure drops are lower. The numerical model was tuned based on the investigation where CoolSelector – dedicated Multi Ejector tests have been compared, comprising the two different tests presented above.

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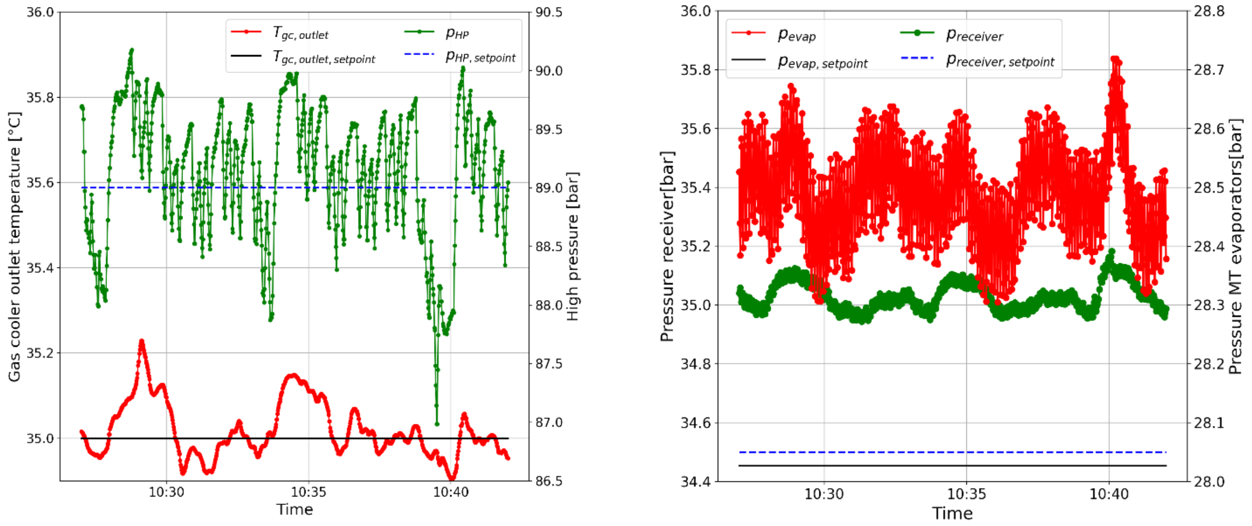


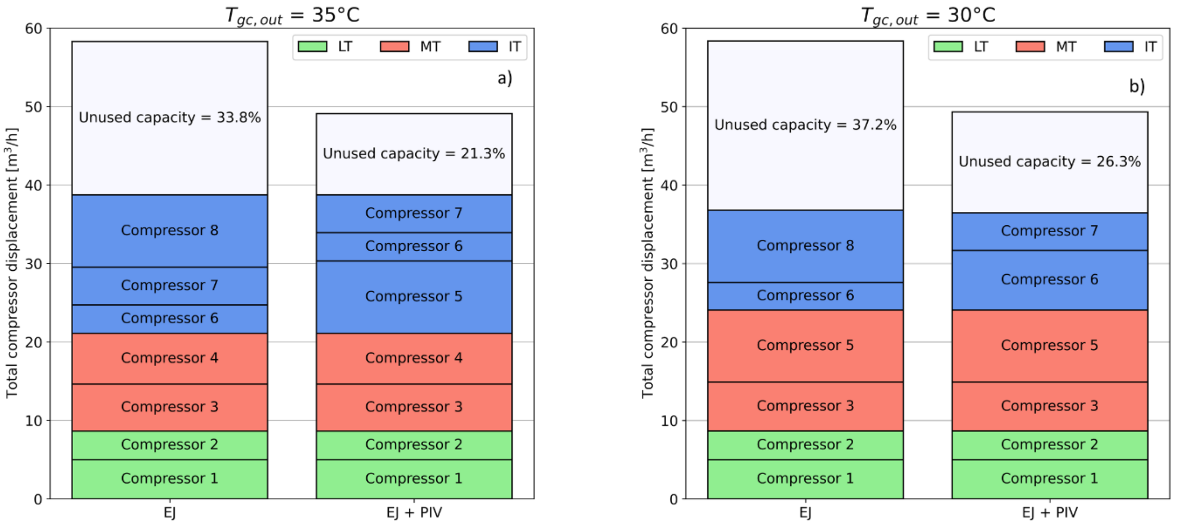
Figure 5: Conditions at the motive nozzle (left) and pressure levels at the suction and discharge port of the ejector (right).

5. RESULTS

In this section the simulation and experimental results will be presented separately and lately discussed. The performance of the Multi Ejector block is the driving force in the current analysis.

5.1. Theoretical results

Figure 6 illustrates the effect of having pivoting compressors in an ejector-supported R744 booster refrigeration system. The types of compressors and how they are distributed into the different groups are presented, as well as the unused capacity in each case. Compressor numbering correspond to that defined in Table 1. It is worth to underline that the unused capacity has been calculated referring to the total displacement installed which comprises all the compressors necessary to supply the cooling loads under different conditions.



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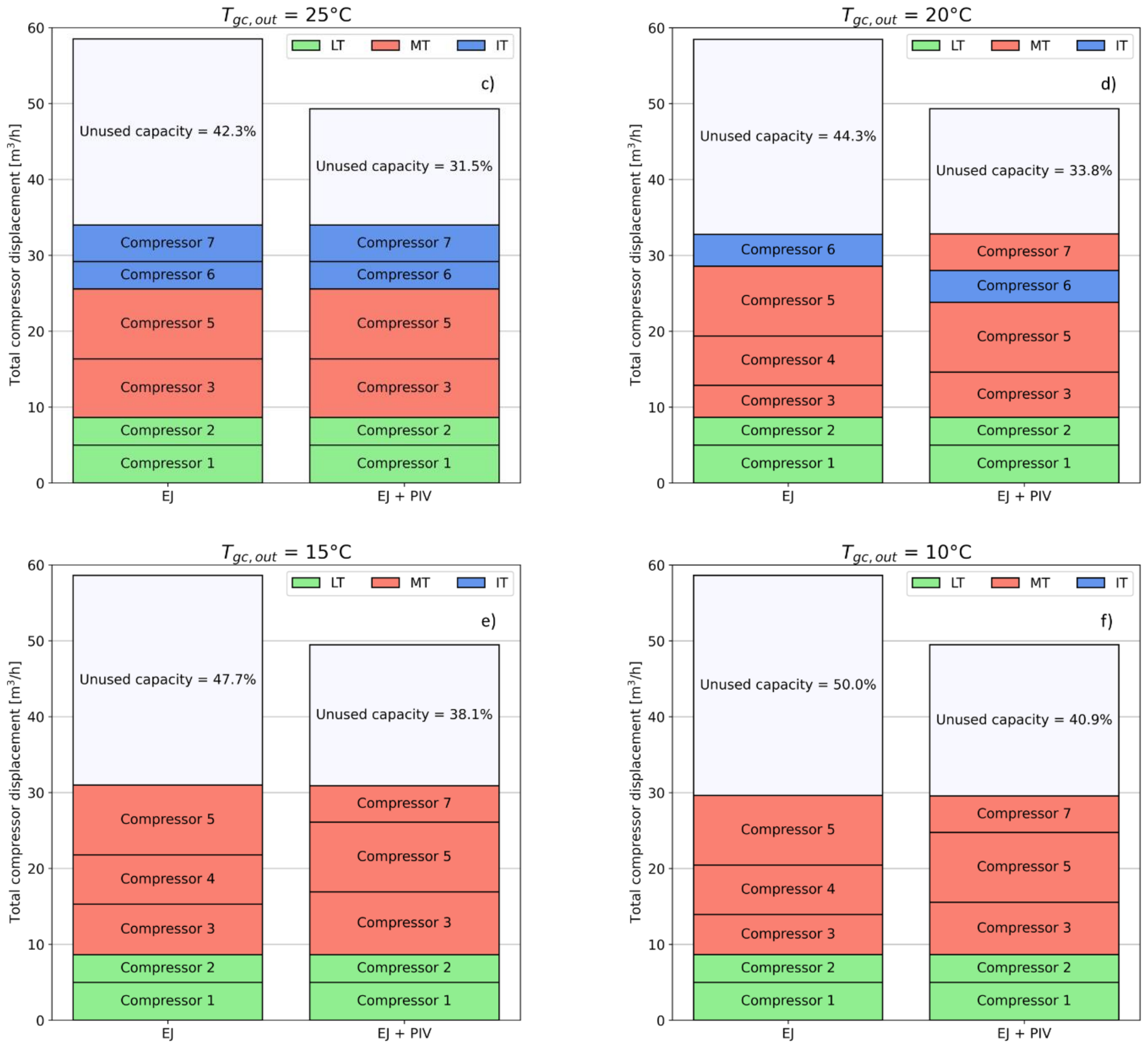

Figure 6: Effect of implementing "pivoting" compressors on the compressor capacity used with ejector as high-pressure control device based on simulation results.

The benefit of implementing pivoting compressors is associated with the unused capacity. The unused MT compressors under summer conditions (case (a), (b) and (c)) due to the amount of vapor formed inside the receiver and further overloading of the IT compressors thanks to the ejector, would be unnecessary to a certain degree in a system with pivoting compressors. On the other hand, during colder conditions (case (c) and (d)) the required capacity on the IT group is getting lower until it totally disappears ((e), (f)). With pivoting compressors under these conditions it is possible to allocate them all at the MT suction group, where they could be needed.

5.2. Experimental results

Figure 7 shows the experimental results for all the cases examined. At the highest gas cooler outlet conditions, case (a), the cooling loads can be supplied with two compressors in each compressor section but running almost at full speed. The results for this case justify what has been claimed before: a small overprediction on the entrainment ratio would move the boundary load between MT-IT in favour of the IT compressor group, requiring the installation of an additional compressor. Consequently, this would affect the total capacity installed and thus the unused capacity value. Unlike the case (a), the other cases are in good agreement with the simulation results, mostly when the ejector is not entraining any flow. The smallest "pivoting" compressor 7 is very useful to follow the load variation under different gas cooler outlet temperatures. If the pivoting features were implemented, six compressors in total would be enough to supply

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the cooling at different gas cooler outlet temperatures and meeting the requirements in terms of evaporating temperatures, ensuring stable conditions over all the measurements.

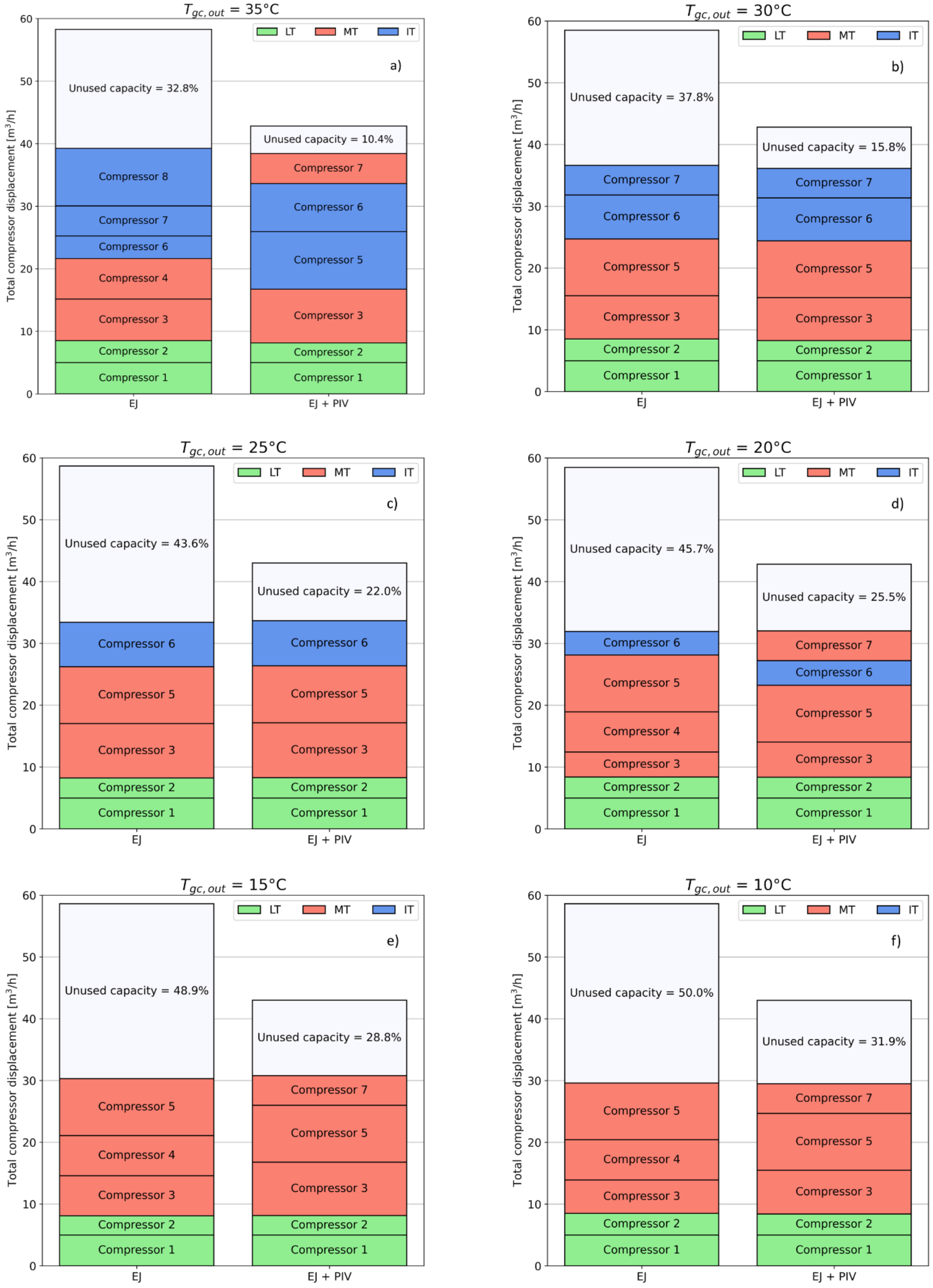

Figure 7: Effect of implementing "pivoting" compressors on the compressor capacity used with ejector as high-pressure control device based on experimental results.

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5.3. Ejector as the main expansion control device

The experimental campaign performed was used to prove the suitability of the Multi Ejector block as the primary component for regulating the discharge pressure in the system. Figure 8 illustrates the high-pressure profile over the measurement for the most extreme temperatures tested. Unlike a pure control of the high-pressure through the HPV, the nature of the Multi Ejector opening features invoked a fluctuation of the pressure. Being the Multi Ejector designed for relative high heat rejection temperatures and constituted by many cartridges which enter in action depending on the capacity required, the profile registered in Figure 8 (right) is justified. Even in this case where there was not a suitable cartridge combination and the ejector cartridges activated changed during the experiment, the Multi Ejector retained the dynamic operation characteristics of the unit and an acceptable discharge pressure control.

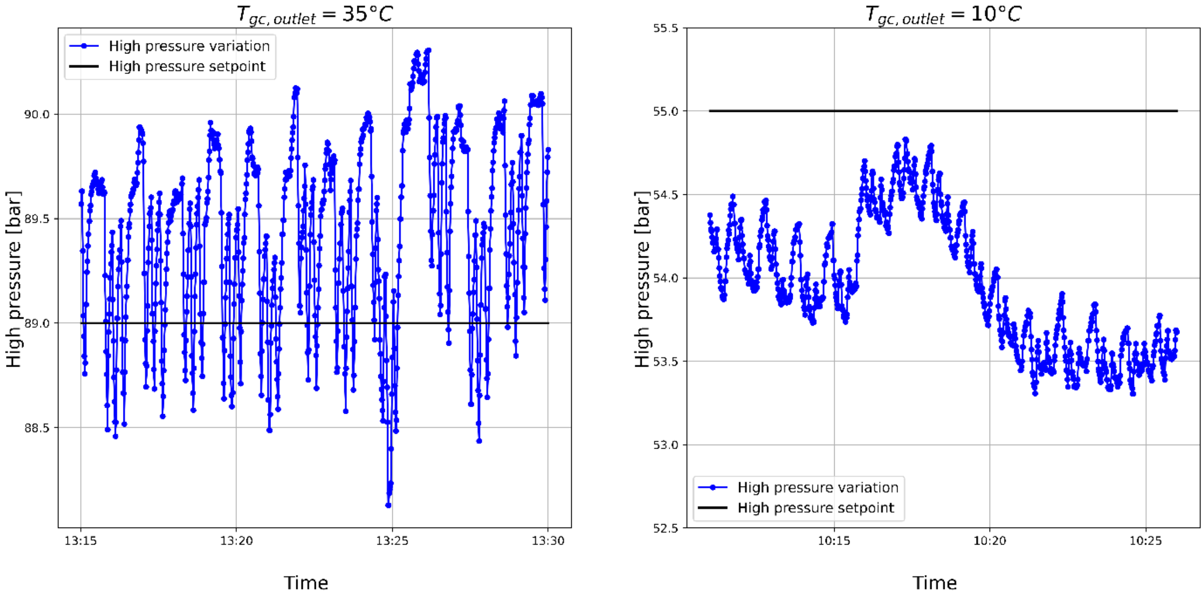

Figure 8: Ejector's response to the high-pressure setpoint as a function of the gas cooler outlet temperature without the use of HPV in parallel.

5.4. LT "pivoting" compressors

Another innovative solution to increase the flexibility of the R744 refrigeration unit is to discharge the LT compressors to the suction line of IT compressors. This functionality would be beneficial in cold regions, where the difference in terms of efficiency between a booster system and parallel compression unit is a disadvantage of the latest. In fact, according to the minimum pressure ratio allowable for the IT compressors, some load can be transferred from MT towards IT group enabling some energy saving. It is also worth to mention another possible implementation: depending on the design of the unit, cooling loads and ambient conditions, the LT "pivoting" could totally turn off the MT compressors while maintaining the desired evaporating level thanks to the ejector. In this study, an experimental comparison between a "pivoting" unit with and without LT compressors is illustrated in Figure 9 for gas cooler outlet temperatures of 20 °C and 15 °C, respectively. At 15 °C (Fig. 9 (right)) part of the flow previously sucked by the MT compressors (coming from the receiver through the FGV) is now delivered to the compressor 6, turning off also compressor 7 on the MT group. This leads to an energy saving around 1.7 kW (7.38 %); the implementation of this technique is therefore a trade-off between operation time at such conditions and increase of complexity of the unit.

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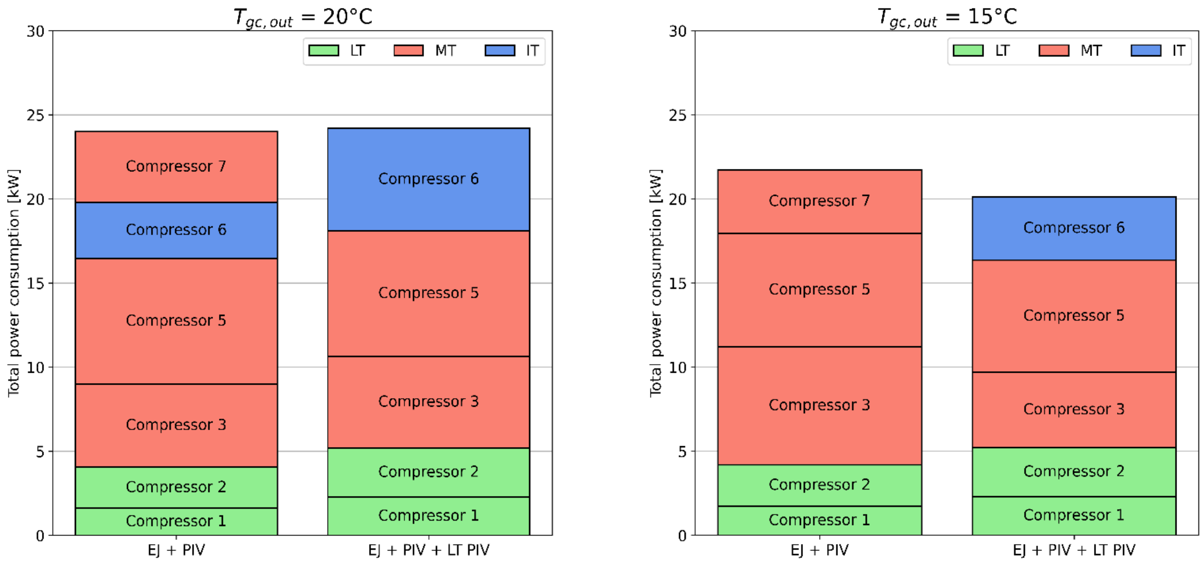

Figure 9:Comparison in terms of power consumption with and without LT “pivoting” functionality.

5.5. Performance with and without the “pivoting” arrangement

Figure 10 presents the comparison in terms of COP for the experimental results between the unit without (baseline) and with “pivoting” compressors. The COP is simply defined as the ratio between the cooling loads (MT and LT) to the total power consumption required by the three compression stages (IT, MT, LT):

$$COP = \frac{Q_{LT} + Q_{MT}}{P_{LT} + P_{MT} + P_{IT}} \tag{1}$$

It can be observed that the effect of pivoting on COP is negligible, and the differences could be reasonably attributed to the regime of frequency of the inverter-driven compressors in each case.

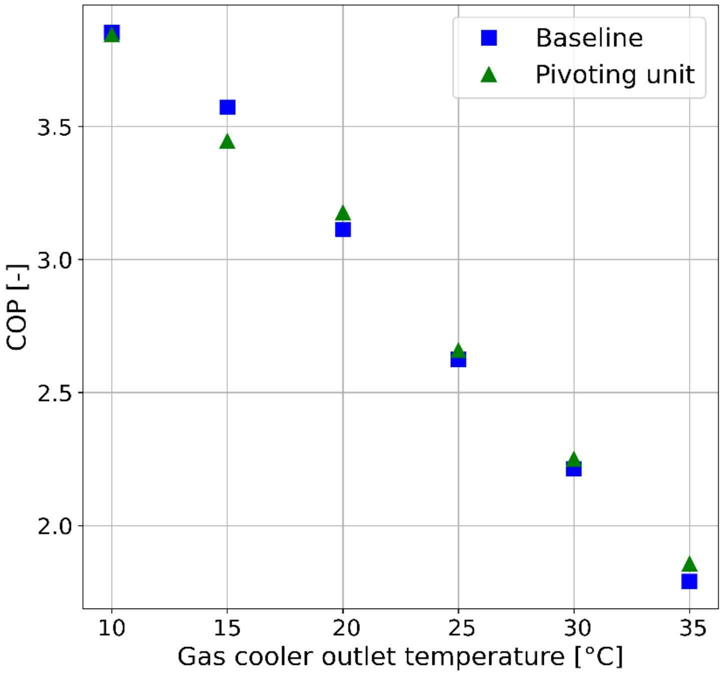

Figure 10: COP comparison between system “pivoting” and no “pivoting” supported.

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6. CONCLUSION

This study explores the impact of having “pivoting” compressors in an ejector-supported R744 booster system for a medium-sized supermarket located in a mild climate. It has been stated that is fundamental to ensure a cost-efficient implementation of ejectors using “pivoting” compressors. The numerical simulation and experimental campaign performed had the goal to evaluate extensively the flexibility of the compressor rack with this new functionality under many different operating conditions and with a look to a possible performance deterioration. The experimental results have proven the importance of predicting accurately the ejector performance due to its effect on the load distribution between the two suction groups (MT – IT). The numerical simulations were adjusted based on a comparison between experimental data – CoolSelector. n fact, “pivoting” has a positive impact on flexibility with reduced installed compressor capacity for an ejector-supported unit, while keeping system efficiency enhancement from ejector. Moreover, the Multi Ejector is a viable solution to regulate the high pressure even during colder conditions. The better utilization of capacity due to the "pivoting" compressors would lead to a reduction of the investment costs, with up to two compressors cut off and thus compensating the cost of the ejectors. In addition, the footprint of the rack would be smaller, and the operation time of each compressor would be broadened which could reduce maintenance needs. The use of LT “pivoting” compressors could be an interesting option to further optimize the unit, depending on the most lasting operating condition. The development of a dedicated control system (hardware & software) will be the next step to extensively analyse the response of the unit under others operating conditions (part-loads).

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NOMENCLATURE

IT	Intermediate temperature	HPV	High-pressure valve
MT	Medium temperature	COP	Coefficient of performance [-]
LT	Low temperature	Ej	Ejector
HP	High pressure [bar]	Piv	Pivoting
gc	Gas cooler	CS	CoolSelector
Q	Cooling load [kW]	P	Power consumption [kW]

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