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# A REVIEW ON RECENT TECHNOLOGICAL ADVANCEMENTS IN MULTI-EJECTOR CONCEPT

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## ABSTRACT

As a consequence of the coming into force of the EU F-Gas Regulation 517/2014, enormous technological developments have been experienced on the part of transcritical R744 supermarket refrigeration systems. These have led to the wide acceptance of multi-ejector based technologies as the most promising hydrofluorocarbon (HFC)-free solutions for commercial refrigeration sector. Approximately 50 stores have been equipped with a multi-ejector block. Furthermore, such an expedient is expected to offer significant electricity savings in other energy-demanding applications (e.g. hotels, gyms) as well, even in warm climates. This work summarizes the evolution of R744 multi-ejector enhanced parallel compression system architectures for supermarket applications. Additionally, their technological aspects as well as the potential energy benefits along with some relevant field/experimental measurements are also presented. Furthermore, the experience gained in the use of the multi-ejector concept in transcritical R744 heat pump technologies is summed up. At last, the persistent challenges needing to be faced are revealed.

Keywords: Ejector, Heat pump, R744, Supermarket, Transcritical $CO_2$ System

## 1. INTRODUCTION

A great interest in refrigeration systems using $CO_2$ as the only refrigerant (R744) is occurring in food retail industry due to the restrictive legislative acts for environment preservation currently in force across the world. The present challenge lies in moving these systems, which are widely used in Northern Europe, to warm areas on global perspective. A first step towards the adoption of such solutions in high ambient temperature countries is offered by parallel compression (Gullo et al., 2016c, 2016b, 2016a; Polzot et al., 2016a). However, Karmapour and Sawalha (2017) recently proved by using some filed measurements that such a solution is suitable only for cold regions. The proliferation of these HFC-free technologies in supermarket applications is thus expected to take place by simultaneously adopting several energy efficient expedients (Girotto, 2017), i.e. parallel compression, overfed evaporators (Minetto et al., 2014a) and multi-ejector concept (Hafner et al., 2012, 2014a). The use of several two-phase ejectors for expansion work recovery operating in parallel is also supposed to open the door to transcritical R744 heat pumping units in many other energy intensive applications (Hafner et al., 2014a).
In this study, the state-of-the-art multi-ejector based solutions for food retail industry and their technological aspects are presented. In addition, the potential energy advantages as well as some noteworthy field/experimental data are also shown. Furthermore, the main findings related to transcritical R744 heat pumping units using multi-ejector block are described. Finally, the remaining challenges needing to be tackled are brought to light.

## 2. MULTI-EJECTOR CONCEPT

Two-phase ejectors are well-established and reliable technologies to copiously enhance the performance of vapour-compression systems. In particular, Lawrence and Elbel (2015) highlighted that the potential enhancements in energy efficiency related to ejector-based technologies are much greater as R744 is used as the only refrigerant compared to those employing conventional working fluids.

Both fixed size ejectors, arranged in blocks and able to provide a step regulation, and variable size ejectors are able to cope with variable load and ambient conditions, typical of commercial refrigeration. In order to guarantee that all the mass flow rate required to satisfy the required cooling load is always available, the multi-ejector concept, relying on the use of several fixed geometry devices of various size and connected in parallel, in combination with parallel compression layout, was proposed (Hafner et al., 2014a). The multi-ejector rack available in the market consists of 4-6 vapour ejectors and, as for supermarket applications, 2 liquid ejectors. Therefore, the expansion work is partially recovered and employed by vapour ejectors for pre-compressing a large amount of refrigerant, leading to higher suction pressures of the compressors. At least one of these ejectors is in operation and the necessary capacity is constantly satisfied by changing their combination, besides guarantying the occurrence of the optimal high-side working conditions in any operating mode. As regards commercial refrigeration sector, further copious energy savings are derived from overfeeding the evaporators with the aid of the liquid ejectors. This permits these heat exchangers to operate at a higher working temperature than conventional dry-expansion evaporators. According to Girotto (2017), a liquid ejector with an efficiency of 8% enhances the overall annual performance by 15%, whereas a vapour ejector with a peak efficiency of 30% would improve it by 5%, depending on the outdoor temperature profile.
It is worth remarking that other ejector-based solutions have been recently launched onto the market, such as the one relying on a spindle controlled with a step motor aimed at accurately meeting the total required capacity. However, only the cross section of the motive nozzle can be varied with respect to the running modes, whereas the mixing and diffuser sections are kept unvaried. This implies that the ejector geometry is adequate only for a specific mass flow/capacity. In addition, a shortage of experimental data capable of proving its energy efficiency as well as its reliability can be currently faced (Girotto, 2017).

## 3. SUPERMARKET APPLICATIONS

In a booster layout with parallel compression, the vapour ejectors lead the suction pressure of parallel compressors to be 3-10 bar as high as that of the medium temperature (MT) compressors in relation to a conventional booster solution. This means that a significant vapour mass flow rate is shifted from the MT to the parallel compressors and then offering a considerable enhancement in the overall energy efficiency particularly at severe running modes. In fact, the former are massively unloaded to the detriment of the latter and considerable energy savings can be achieved (Hafner et al., 2016; Fredslund et al., 2016). At the same time, liquid ejectors recirculate excess liquid coming out from the evaporators. Banasiak et al. (2015) designed, manufactured and carried out a performance mapping of a multi-ejector module for supermarket applications. Schönenberger (2016) and Minetto et al. (2015) suggested adopting an internal heat exchanger between the suction line of the low temperature (LT) compressors and the liquid exiting the intermediate receiver to overfeed the LT evaporators as well. Shecco (2016) estimated that R744 multi-ejector enhanced parallel compression technologies are currently, at worst, 10% more costly than conventional refrigeration plants.

### 3.1 State-of-the-art layouts

Fully-integrated R744 supermarket refrigeration systems equipped with multi-ejector module (Figure 1) are becoming mainstream HFC-free technologies worldwide. In fact, these are expect to considerably bring total investment, maintenance and running costs down (Hafner et al., 2015). As a consequence, “next generation” of these solutions will be based on both the application of the all-in-one concept and the use of two multi-ejector blocks (i.e. one dedicated to air conditioning reclaim and the other to refrigeration purposes) offering a pressure lift (i.e. difference between outlet and suction pressure) of 15 bar (Hafner et al., 2015).
Many researchers (Hafner, 2017; Banasiak et al., 2015; Hafner et al., 2015; Minetto et al., 2015; Pardiñas et al., 2017a, 2017b) also suggested interchanging the MT and parallel compressors (i.e. principle of pivoting) with respect to the operation conditions to further enhance the overall performance. This means that the compressors can be linked to either the MT or the parallel suction group by using on/off valves being upstream of them (Hafner, 2017). Also, Pardiñas et al. (2017a) theoretically proved that further energy advantages can be obtained by connecting the LT compressors to the intermediate pressure (IP) accumulator. The “all-in-one” refrigeration system represented in Figure 2 applies this principle as well as presents a multi-ejector module dedicated to air conditioning (AC) purposes. Such a technology is a state-of-the-art solution for supermarkets located in Southern Europe or Middle East (Hafner, 2017).

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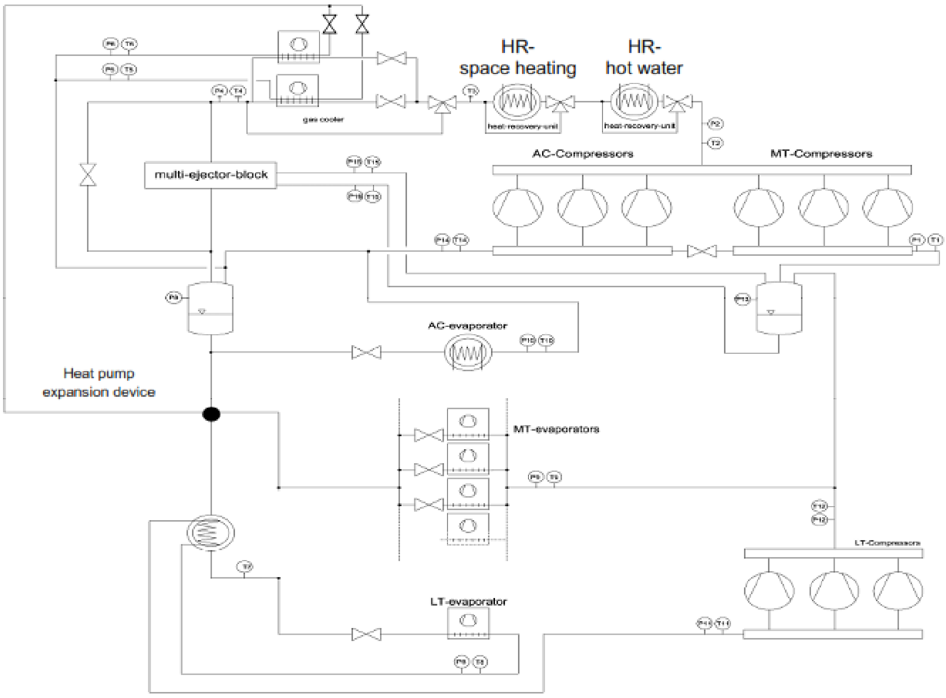


**Figure 1: Fully-integrated R744 multi-ejector enhanced parallel compression system installed in a supermarket located in Spiazzo (Italy) (Hafner et al., 2016).**

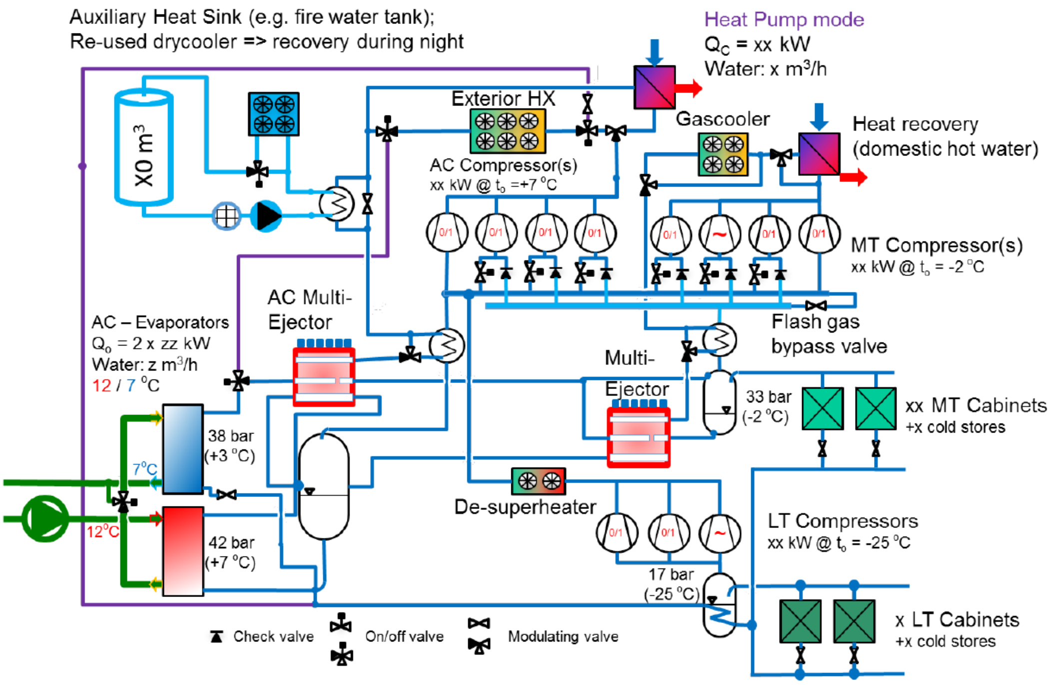


**Figure 2: Fully-integrated R744 refrigeration system for supermarkets located in warm regions (Hafner, 2017).**

Hafner (2107) recently recommended avoiding a secondary fluid between the refrigeration plant and the AC/heating unit, using R744 in direct cooling and heating fan coils and air curtains installed inside the building. This would allow benefiting from many advantages, such as reduction in the number of heat exchangers, decrease in the investment costs, greater energy efficiency, no corrosiveness issues. A refrigeration system layout relying on this technique is shown in Figure 3. This enables to recover the expansion work in the ejectors from the AC operation too. The adequate amount of R744 is obtained with the aid of modulating 2/3-way-valve downstream of the ejectors. In heating mode, the gas cooler is by-passed and thus the heat is rejected directly into the building by the unit (fan coil or air curtain).

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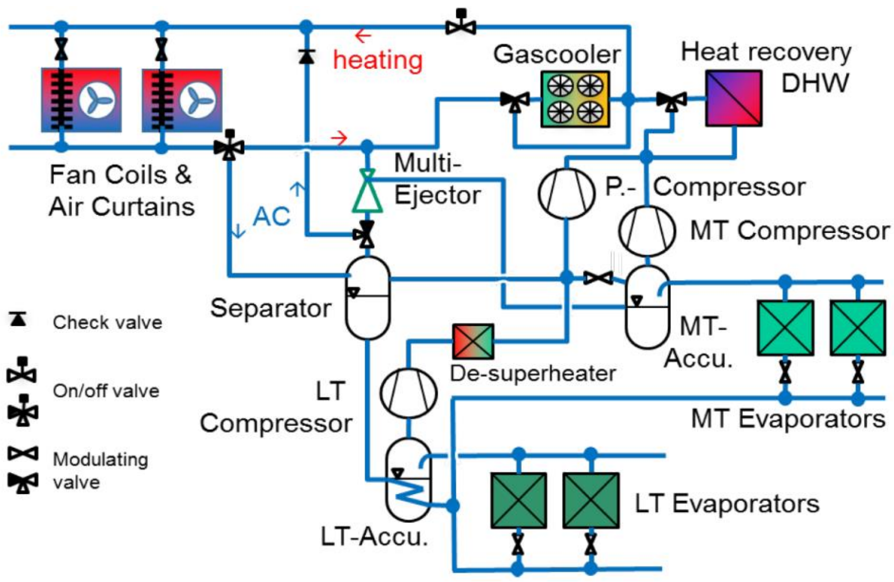


**Figure 3: Integration of direct heating and cooling fan coils and air curtains in a transcritical R744 supermarket refrigeration system (Hafner, 2017).**

### 3.2 Estimated energy benefits

According to Hafner et al. (2012), the implementation of the multi-ejector concept in a supermarket located in Southern Europe allows attaining an energy conservation by about 11% compared to a conventional booster technology.

Minetto et al. (2014b) theoretically estimated an energy saving by 22.5% on the part of a R744 multi-ejector enhanced parallel compression system over a basic "$CO_2$ only" system in a food retail store in the South of Italy.

The dynamic simulation model developed by Hafner at al. (2014) estimated typical COP increments in the refrigeration mode by 17% in Athens (Greece), 16% in Frankfurt (Germany) and 5% in Trondheim (Norway) in summertime, while the ones related to wintertime were between 20% and 30% compared to a conventional booster unit.

Gullo et al. (2017a) theoretically estimated that the multi-ejector concept permits consuming between about 20% and 27% less electricity than a R404A unit in an average-size supermarket located in the South of Europe. At the same boundary conditions, parallel compression offers, at best, an energy saving by 6.4%. Also, a R744 multi-ejector enhanced parallel compression system integrated with AC equipment leads to energy savings ranging from 15.6% to 26.2% over conventional HFC-based solutions, depending on the size of both the AC unit and the supermarket, as well as on the climatic conditions.

Gullo et al. (2017b) theoretically evaluated that the adoption of the multi-ejector concept features energy conservations from 17.8% (in Oslo, Norway) to 26.7% (in Athens) over a conventional booster solution and from 16.9% in (London, UK) to 23.4% (in Oslo) in relation to a solution with parallel compression. Compared to a R404A system, this allows reducing the annual intake between 24.6% (in Athens) and 37.1% (in Oslo). Furthermore, the researchers showed that, unlike the solution with parallel compression, such a solution permits "$CO_2$ only" supermarket refrigeration plants to be energy competitive with a R404A unit at outdoor temperatures up to 40 °C. It is anyhow worth reminding that R404A systems will not be allowed since 2022 and alternatives based on cascade or indirect loop arrangements synthetic will be likely to be less efficient, as illustrated in a recent report by the European Commission (2017).

In some conditions the required heating load can be only satisfied by transcritical operations of the refrigeration system (Polzot et al., 2016b). This additionally foster the adoption of the multi-ejector concept as this offers a potential of energy conservation (Schönenberger et al., 2014; Hafner et al., 2014a; Hafner et al., 2014b). As an example, Gullo and Hafner (2017) theoretically showed that a R744 multi-ejector enhanced parallel compression system features between 57.8% and 100.1% as high as total Coefficient of Performance ($COPs_{total}$) values than separated HFC units at external temperatures ranging from -10 °C up to 5 °C.

The theoretical investigation by Kvalsvik et al. (2017) revealed that a R744 supermarket refrigeration system relying on two multi-ejectors blocks has 53% higher energy consumption than separated R410A-based

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solutions at the design external temperature of 45 °C (i.e. Indian climate context). However, the energy advantages related to the adoption of overfed evaporators were not taken into account, as well as the assessment should have been carried out on an annual basis.

Pardiñas et al. (2017a) theoretically compared the performance of various booster refrigeration system layouts integrated with the AC equipment in a conventional Norwegian food retail store. The investigation revealed that the adoption of a multi-ejector rack is energy beneficial at outdoor temperatures above 25 °C (Figure 4). Additional energy savings are offered by employing an AC multi-ejector rack (8.3% at 30 °C and 8.6% at 25 °C).

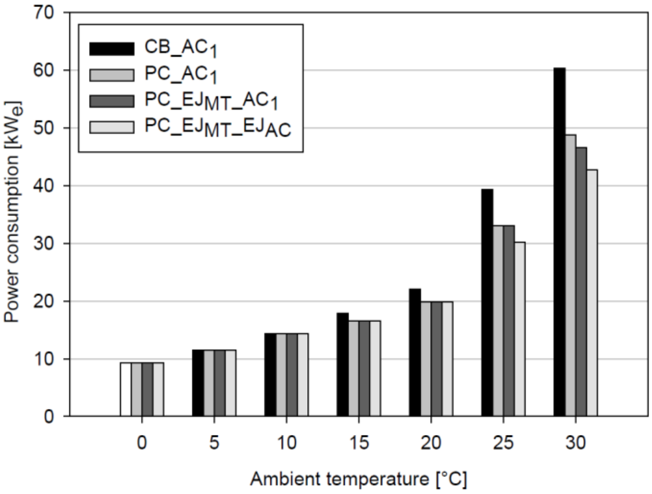


**Figure 4: Electric power input of a conventional booster system (CB_AC), booster system with parallel compression (PC_AC), multi-ejector enhanced parallel compression system with ($PC\_EJ_{MT}\_EJ_{AC}$) and without ($PC\_EJ_{MT}\_AC$) AC multi-ejector block in a typical Norwegian supermarket (Pardiñas et al., 2017a).**

The theoretical study implemented by Pardiñas et al. (2017b) in steady state operations showed that a R744 ejector supported parallel compression with and without AC multi-ejector module perform similarly in subcritical running modes. The assessment was carried out by considering a Norwegian medium-sized food retail store ($\dot{Q}_{MT}$ = 60 kW, $\dot{Q}_{LT}$ = 10 kW, $\dot{Q}_{AC}$ = 45 kW, design outdoor temperature of 30 °C). The authors highlighted that the improvement in the overall energy efficiency related to the AC multi-ejector block has to compensate the additional cost as well as the complicated system performing the discharge pressure control. Furthermore, the system without AC multi-ejector module and applying the pivoting strategy was indicated as a more reasonable solution since AC evaporating pressures could be maintained at around 35 bar.

The theoretical study by Gullo and Hafner (2017) highlighted that a R744 multi-ejector enhanced parallel compression solution performs better than R1234ze(E)/R744 indirect arrangements, even in warm climates. The authors estimated that the former consumes at least up to 20.9%, 16.7% and 9.3% in Chicago (USA), Atlanta (USA) and Miami (USA) less electricity over the latter, respectively.

### 3.3 Experimental results and field measurements

The first installation (Schönenberger et al., 2014) revealed that the multi-ejector concept enables an energy saving by 14% compared to three similar systems equipped with parallel compression over the same period of time in the Swiss climate context, as shown in Figure 5.

The data from field by Schönenberger et al. (2014) and Hafner et al. (2014b) highlighted that the MT evaporators can successfully switch from superheated to overfed mode and vice versa as well as from subcritical to heat recovery mode and vice versa. Moreover, the compressors face no dangers in terms of liquid slugs to the compressors thanks to presence of the medium pressure (MP) receiver as well as the number of ejectors has to be more than 3 to be able to reach the heat rejection pressure set points without too many on/off switches of these devices. At last, the researchers proved that the control system can appropriately handle possible blockages of an ejector nozzle.

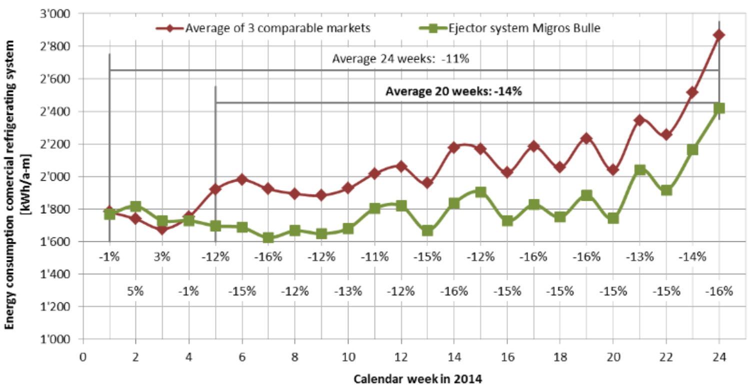


**Figure 5: Comparison of the energy consumption of transcritical $CO_2$ booster refrigerating technologies with and without ejector support in Switzerland (Schönenberger et al., 2014).**

The currently available field measurements demonstrate that the adoption of a multi-ejector module allows increasing MT and LT respectively by 6 K and by 8 K all year round (Figure 6) and, consequently, decreasing the frost formation and number of defrost cycles

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compared a conventional technology (Hafner et al., 2014b; Schönenberger et al., 2014; Schönenberger, 2016; Girotto, 2017).

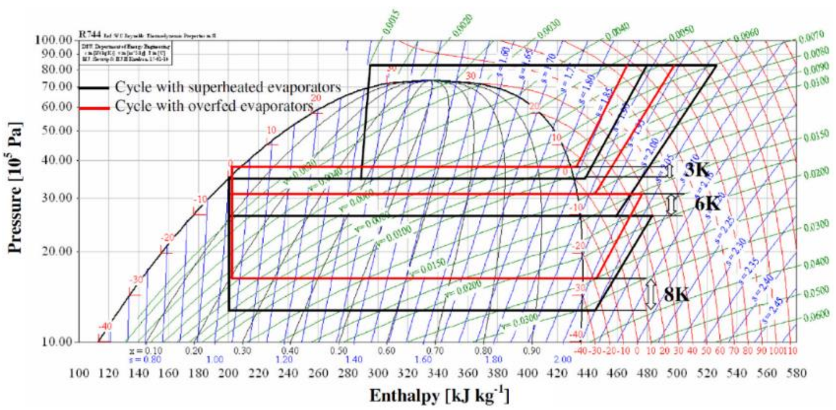


**Figure 6: Comparison between the thermodynamic cycle with superheated evaporators and that with overfed evaporators (Girotto, 2017).**

The field measurements collected by Schönenberger et al. (2014) and Hafner et al. (2014b) revealed that energy conservations by 10% over the solution with parallel compression and by 18% compared to a conventional booster unit can be achieved in a large food retail store located in the region of Fribourg (Switzerland) in wintertime, respectively.

Banasiak et al. (2015) experimentally showed that the ejector efficiencies above 0.3 can be attained in a broad range of the investigated running modes. The authors found the motive nozzle mass flow rate to be depending on the inlet density and inlet pressure (Figure 7a). It was also brought to light that the optimal operation conditions of an ejector having a given geometry can be achieved by varying the pressure ratio (i.e. the ratio of the ejector outlet pressure to the suction pressure) as a function of the heat sink conditions in the gas cooler (Figure 7b). In addition, Banasiak et al. (2015) highlighted that the evaluated ejector efficiencies were higher than those previously collected. On the other hand, the overall multi-ejector efficiency is progressively penalized as the expanded mass flow rate increases due to the growing stream irreversibilities (e.g. imperfect mixing of individual flows coming out of the ejectors), although the recorded values were estimated to be above 0.2. Finally, it was discovered that liquid ejectors need to be individually designed.

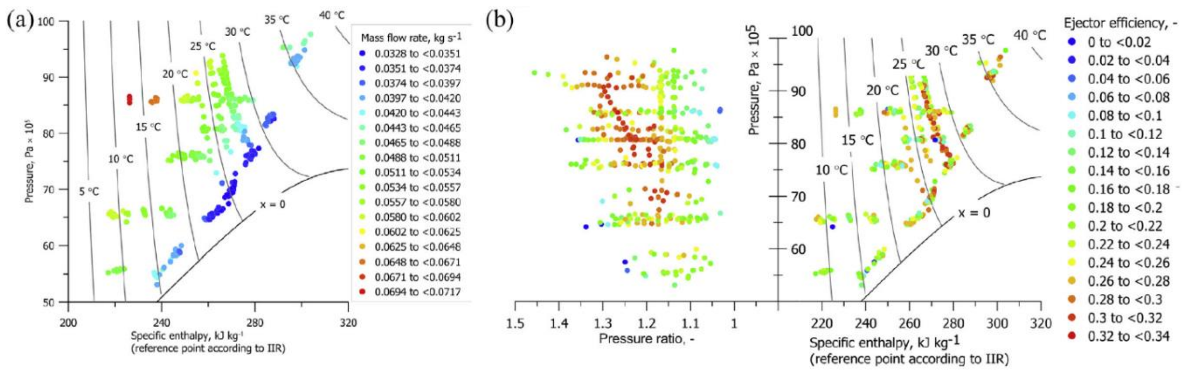


**Figure 7: (a) Motive nozzle mass flow rate as a function of the motive nozzle inlet conditions for one of the investigated ejectors; (b) Ejector efficiency as defined by Elbel and Hrnjak (2008) as a function of the motive nozzle inlet conditions and pressure ratios for one of the investigated ejectors (Banasiak et al., 2015).**

The filed measurements collected by Fredslund et al. (2016) in various locations revealed that energy conservations from 10% to 15% for a solution integrated with the AC equipment at approximately 30 °C can be accomplished. Also, in case of oil return issues, such a multi-ejector based technology with no integration with the AC unit is capable of guarantying an energy saving by 4% at about 27 °C. Finally, the authors proved that vapour ejector efficiencies measured in the laboratory are comparable to those estimated from real installations (and above 0.25).

The experimental investigation by Haida et al. (2016) pointed out that the use of the multi-ejector module leads to increments in COP and exergy efficiency up to 7% and 13.7% compared to the solution with parallel compression. Efficiencies of the multi-ejector rack up to 0.33 were assessed as a function of the pressure lift and the motive and suction conditions. In addition, the authors highlighted that it is necessary to mutually consider the multi ejector block and the compressor rack interactions when designing the refrigeration unit.

Hafner et al. (2016) gathered data from field related to an integrated R744 multi-ejector enhanced parallel compression system operating in Spiazzo (Italy) between the 1st of May and the 30th of October 2015 at external temperatures ranging from 22 °C to 35 °C. The researchers evaluated energy conservations between 15% and 30% compared to the solution with parallel compression depending on the AC demand and outdoor temperature. Also, the measured values of pressure lift ranged between 5 bar and 10 bar.

Schönenberger (2016) presented some data from field showing that energy savings from 15% to 25% can be attained with a multi-ejector solution compared to a system with parallel compression. These are strongly depending on the heating load requirement, application and climate.

A R744 multi-ejector enhanced parallel compression system was lately adopted in a supermarket in Georgia (USA). This was found to increase the peak energy savings by 11.3% and between 15% and 23% in non- and optimized running modes, respectively (www.r744.com).

The R744 ejector supported parallel vapour compression unit installed in a hypermarket located in Timisoara (Romania) in 2015 offers an energy conservation up to 13% in relation to a system with parallel compression (Frigo-Consulting LTD, 2015).

The integrated multi-ejector based R744 technology adopted in Italy's largest hypermarket in Milan presents about 50% lower energy consumption over more conventional installations (Danfoss, 2016).

### 3.4 Technological aspects

Banasiak et al. (2015) experimentally proved that the high pressure can be satisfactorily controlled by a multi-ejector module in commercial refrigeration applications. As depicted in Figure 8, in fact, the researchers assessed similar profiles of the high pressure control error caused by a rapid change in both load and outdoor temperature between a standard high-pressure electronic expansion valve (HVP) and a multi-ejector block.

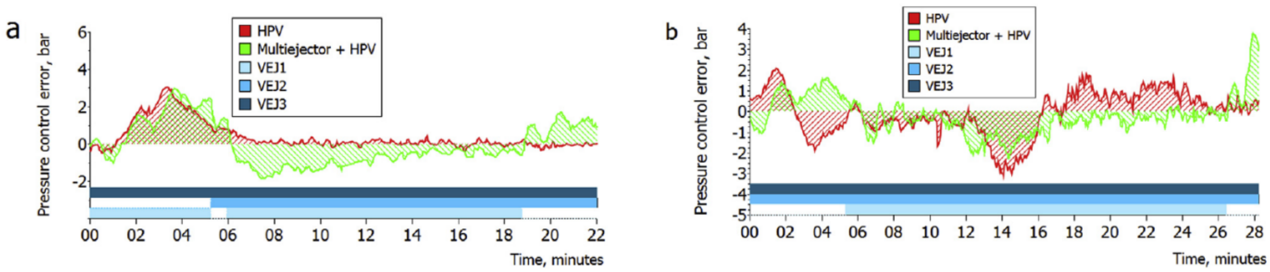


**Figure 8: Deviation between the actual value and set-point value for the heat rejection related to a rapid change in load (a) and in outdoor temperature (b) (Banasiak et al., 2015).**

As regards the oil management, this can be appropriately implemented both within the liquid separator and upstream of the gas cooler (Banasiak et al., 2015; Hafner et al., 2016). Also, it was found that its control system can be effectively performed (Banasiak et al., 2015, 2014; Hafner et al., 2016, 2014b; Schönenberger et al., 2014; Schönenberger, 2016).

The substantial use of the parallel compressors leads to great overall energy efficiencies as well as to decrements in their maintenance issues all over the year (Minetto et al., 2014b).

Schönenberger (2016) experimentally showed that the number of the compressor on-off cycles are lower in comparison with conventional solutions.

The geometrical parameters substantially affect the performance of an ejector with respect to a given range of running modes (Kriezi et al., 2015, 2016). As a consequence, Kriezi et al. (2016) recommended using a liquid ejector designed for summer operating regime and another for winter operating conditions due to the highly fluctuating needs of supermarket applications. Ejectors aimed at vapour removal can appropriately pump some liquid in summertime.

The experimental evaluation by Bodys et al. (2017) proved that a multi-ejector rack offers great and stable performance over the entire range of the investigated operation conditions for supermarket applications.

Girotto (2017) suggested that many advantages can be related to the adoption of a R744 multi-ejector enhanced parallel compression system, such as a considerable reduction of the compressor discharge temperature leading to conspicuous benefits to the oil lifetime as well as to the de-superheater for heat recovery. The protection against liquid in the compressor suction manifolds is also considerable and the total installed swept volume is reduced compared to a single compression system. Furthermore, a simplified control of evaporators can be performed and a great global energy efficiency at outdoor temperatures up to between 40 °C and 42 °C is achieved.

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## 4. HEAT PUMP APPLICATIONS

Thanks to the peculiar properties of R744, such a refrigerant is particularly fitted for water heating in various applications (Nekså et al., 1998; Hafner, 2015; Polzot et al., 2016a, 2016b). However, reversible transcritical R744 heat pumping units are still limited to niche sectors in warm regions due to the considerable performance penalizations occurring in AC mode (Minetto et al., 2016). Minetto et al. (2016) suggested the adoption of a two-phase ejector to permit a $CO_2$ heat pump system to achieve the same seasonal efficiency as a R410A unit in residential applications located in moderate climates (i.e. north-east of Italy). Additional benefits are expected by applying improvement strategies similar to those suggested for supermarkets (i.e. multi-ejector concept adoption, direct heating and cooling) (Hafner et al., 2014a; Minetto et al., 2016).

Boccardi et al. (2017) carried out a sensitivity analysis on a multi-ejector $CO_2$ heat pump water heater involving the ejector area ratio, the compressor frequency and the external temperature. The results revealed the existence of an optimum multi-ejector configuration, as presented in Figure 9a. Also, the assessment indicated that the optimal ejector performance does not coincide with the best performance in terms of COP and heating capacity (Figure 9b). This implies that the performance of the ejector can be enhanced by improving its design. Finally, it was found that, with respect to the outdoor temperature, it is necessary to shift from an ejector configuration to another so as to maximize the performance (Figure 9c).

Boccardi et al. (2016) estimated that the throttling losses can be reduced by 46% by adopting the multi-ejector concept over the investigated operation conditions. However, the enhancement of the overall exergy efficiency is, at best, equal to 9% compared to the basic system.

To conclude, ejector efficiencies lower than the values published in the scientific literature were reported in both the investigations by Boccardi et al. (2016, 2017). This was due to the fact that a multi-ejector block designed for refrigeration purposes (i.e. featuring higher pressure lift than for AC applications) was employed. However, in case of significant loads of domestic hot water (DHW), the reversible R744 heat pumping units for simultaneous heating, AC and DHW and equipped with multi-ejector block, are believed to be very promising technologies. Experimental data will be provided through MultiPACK project (www.ntnu.edu/multipack).

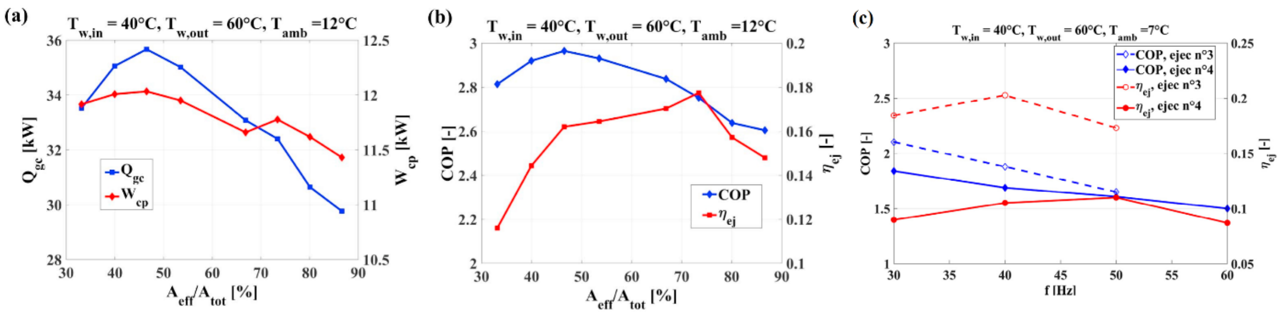


**Figure 9: (a) Heating capacity (left) and compressor work (right) variations as a function of the overall ejector cross section; (b) COP (left) and ejector efficiency (right) variations as a function of the overall ejector cross section; (c) COP (left) and ejector efficiency (right) as a function of the compressor frequency (Boccardi et al., 2017).**

## 5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The current experience in multi-ejector based systems for supermarket applications suggests that these technologies are a market-ready alternative to HFC systems offering great energy savings in any climate context. In addition, it has been widely proved the reliability as well as the feasibility of such solutions. On the other hand, future experimental work on the evaluation of the energy and economic advantages associated with the use of two different multi-ejector modules, with the direct heating and cooling fan coils and air curtains and with the principle of pivoting is still required. Additionally, further experimental assessments on integrated $CO_2$ multi-ejector enhanced parallel compression systems in hot climates (e.g. India) need to be performed.

As regards heat pumping applications, the multi-ejector concept is at an earlier development stage, although some field installations will be soon ready for performance assessment. The proliferation of these technologies will be strongly related to the energy benefits achievable by adopting a multi-ejector block as well as simultaneously overcoming the secondary fluid penalization with the aid of direct heating and cooling technique, especially in warm areas.

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## NOMENCLATURE

| | | | |
|---|---|---|---|
| *AC* | air conditioning | *COP* | coefficient of performance (-) |
| *DHW* | domestic hot water | *HFC* | hydrofluorocarbon |
| *HVP* | high pressure electronic expansion valve | *IP* | intermediate pressure (bar) |
| *LT* | low temperature (°C) | *MP* | medium pressure (bar) |
| *MT* | medium temperature (°C) | $\dot{Q}$ | capacity (kW) |

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