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# Multi-Ejector Concept: A Comprehensive Review on its Latest Technological Developments

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**Abstract:** The adoption of the EU F-Gas Regulation 517/2014 and the resulting development of the multi-ejector concept have led carbon dioxide to take center stage as the sole refrigerant (R744) in several applications. Therefore, a knock-on effect on the number of supermarkets relying on "$CO_2$ only" refrigeration systems has been experienced. Additionally, a global consensus of commercial multi-ejector based R744 units is also intensifying as a consequence of both the promising results obtained and the other measures in force for environment preservation. Furthermore, the multi-ejector concept is expected to offer significant energy savings in other high energy-demanding buildings (e.g., hotels, gyms, spas) as well, even in warm climates. In this investigation, the evolution of R744 ejector supported parallel vapor compression system layouts for food retail applications was summed up. Furthermore, their technological aspects, the results related to the main theoretical assessments and some relevant field/laboratory measurements were summarized. Also, the experience gained in the adoption of the multi-ejector concept in transcritical R744 vapor-compression units aimed at other energy intensive applications was presented. Finally, the persistent barriers needing to be overcome as well as the required future work were brought to light.

**Keywords:** air conditioning; chiller; $CO_2$; commercial refrigeration; heat pump; heat recovery; industrial refrigeration; R744; transcritical vapor-compression system; two-phase ejector

## 1. Introduction

The implementation of the EU F-Gas Regulation 517/2014 [1] on fluorinated greenhouse gases (F-gases) has prompted the need to discontinue their use and substitute these working fluids with less environment-damaging alternatives. This holds particularly true for the sector involving high energy-demanding buildings (e.g., supermarkets, hotels, gyms), as the fulfillment of their refrigeration, cooling and heating (RC&H) needs causes significant indirect contributions to global warming as well. Furthermore, as a consequence of the ongoing sharp hydrofluorocarbon (HFC) quota reduction [1], the global refrigeration sector is facing an ever-growing shortage of "old" synthetic refrigerants (e.g., R404A, R507A) as well as a dramatic price rises in others (including new man-made working fluids, e.g., R448A, R449A, in addition to R404A, R507A and R410A) [2]. Also, in parallel with the coming into force of the F-Gas Regulation 517/2014 in Europe, a commitment on global scale to fight against climate change has been performed through the adoption and ratification of the Kigali amendment to the Montreal Protocol [3].

Carbon dioxide is perceived as a long-term working fluid for various RC&H applications [4], being non-flammable, non-toxic and offering favorable environmental, i.e., negligible Global Warming Potential (GWP) as well as zero Ozone Depletion Potential (ODP), and thermo-physical properties [5]. R744 is also inexpensive in comparison with man-made refrigerants. As suggested in [6], "$CO_2$ only" (or transcritical $CO_2$) RC&H solutions are accepted as viable and sustainable candidates in several sectors (e.g., supermarkets, vehicle air conditioning and heat pump units, domestic hot water heat pump systems and industrial applications). As examples:

- It was estimated that 9000 supermarkets relying on transcritical R744 systems were operating in Europe in 2017 [7]. However, it is expected that these units will be 25,000 in 2020 [4] and 55,000 in 2025 [4];
- The government subsidies has led "$CO_2$ only" heat pump units for domestic hot water (DHW) purposes to become standard in Japan;
- Transcritical R744 solutions are gaining ever-growing attraction in industrial refrigeration applications featuring large cooling loads [4].

However, the persistent challenge lies in moving "$CO_2$ only" vapor-compression units to warm regions worldwide. The implementation of the aforementioned legislative acts has accelerated innovation for large-scale "$CO_2$ only" RC&H solutions, giving rise to technologies aimed at achieving this target. Among these, the ever-growing uptake of commercial "$CO_2$ only" around the world can be ascribable to the conception of the multi-ejector concept [8], conceived by Hafner et al. [9,10]. Also, its adoption is supposed to offer considerable energy conservations in other high energy-demanding buildings (e.g., hotels, gyms, spas) too, even in warm weathers.

In this investigation, the state-of-the-art multi-ejector based solutions for supermarkets and their technological aspects are presented. Furthermore, the potential energy benefit as well as some relevant field/laboratory data are shown. Also, the findings associated with the implementation of the multi-ejector concept in other applications are described. At last, the remaining challenges requiring to be faced are summarized.

## 2. Multi-Ejector Concept

The performance of basic "$CO_2$ only" vapor-compression systems is significantly more sensitive to cooling medium temperature than HFC-based units. As a consequence of the low critical temperature of R744 (i.e., about 31 °C), in fact, transcritical running modes can commonly take place. These cause a large exergy destruction during the throttling process [11], which negatively impacts on the overall efficiency of the system. On the other hand, the significant irreversibilities associated with the expansion valve induce to take into considerations expansion work recovery devices, such as expanders and two-phase ejectors. Their favorable contribution is, in fact, much more relevant than in traditional HFC applications, in which the inefficiencies related to the throttling process are more limited. In the last years, two-phase ejectors have been gaining popularity thanks to their intrinsic simplicity. In general terms, it has been shown that the implementation of a two-phase ejector leads to greater opportunity for energy efficiency improvement [12]. A simple transcritical R744 vapor-compression unit employing an ejector aimed at expansion work recovery is sketched in Figure 1. The refrigerant coming out of the gas cooler/condenser (thermodynamic state 3, identifying the high pressure) is expanded and accelerated through the motive nozzle (thermodynamic state 4). Due to the pressure difference between the expanded refrigerant and the working fluid exiting the evaporator (thermodynamic state 10, identifying the low pressure), the low pressure stream is entrained into the suction nozzle (thermodynamic state 5). Both streams are then mixed in the mixing chamber (thermodynamic state 6) and a part of the remaining kinetic energy of R744 is converted into a pressure increment via the diffuser (thermodynamic state 7, identifying the intermediate pressure). The adoption of a two-phase ejector in place of an expansion valve permits benefiting from two main energy advantages: (i) rise in refrigerating effect as the refrigerant enters the evaporator at lower vapor quality and enthalpy; (ii) decrease in compressor power input since the refrigerant is pre-compressed by the ejector from the evaporator pressure to the intermediate one (IP).

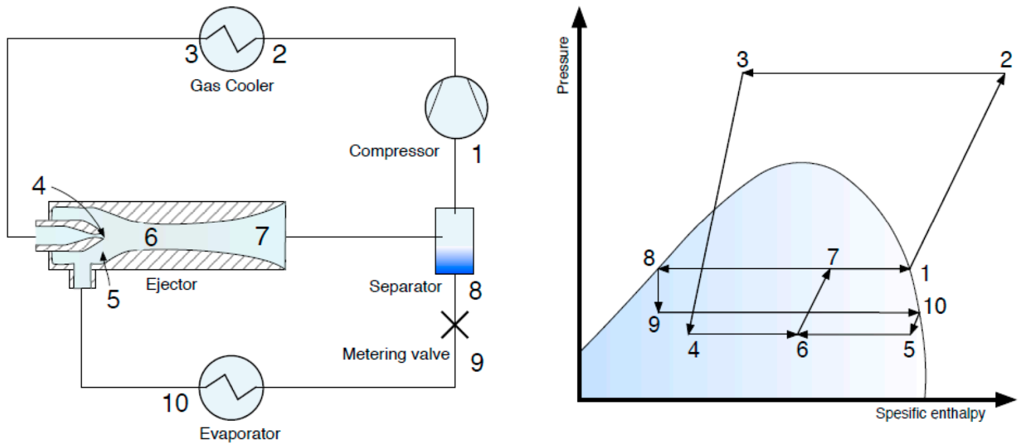


**Figure 1.** Schematic of a simple transcritical R744 vapor-compression system equipped with a two-phase ejector for expansion work recovery (left-hand side) and its p-h diagram (right-hand side) [13].

The performance of an ejector for expansion work recovery is commonly described with the aid of 4 metrics, i.e., mass entrainment ratio ($\omega$), suction pressure ratio ($\Pi$), pressure lift ($P_{lift}$) and expansion work recovery efficiency, being generally indicated as ejector efficiency ($\eta_{ejector}$). The mass entrainment ratio (Equation (1)) refers to the ratio of the suction mass flow rate to the motive mass flow rate and evaluates the ability of the ejector to entrain (or pump) the refrigerant:

$$\omega = \frac{\dot{m}_{suction\ nozzle}}{\dot{m}_{motive\ nozzle}} \quad (1)$$

The suction pressure ratio (Equation (2)) and the pressure lift (Equation (3)) assess the ratio of the ejector outlet pressure to the ejector suction pressure and difference between the ejector outlet pressure and the ejector suction pressure, respectively. These are employed for quantifying the lift that the ejector can provide to the working fluid.

$$\Pi = \frac{P_{diffuser\_outlet}}{P_{suction\ nozzle\_inlet}} \quad (2)$$

$$\mathrm{P_{lift}} = P_{diffuser\_outlet} - P_{suction\ nozzle\_inlet} \quad (3)$$

The ejector efficiency (Equation (4)) defines the actual amount of work recovered by the ejector with respect to the overall work recovery potential. As suggested in [14], this can be computed as the power used for compressing the suction stream isentropically from suction inlet to diffuser outlet pressure divided by the theoretical maximum amount, which could be recovered via an isentropic expansion of the motive stream from motive inlet to diffuser outlet pressure.

$$\eta_{ejector} = \frac{\dot{W}_{recovered}}{\dot{W}_{recoverable\_max}} = \omega \cdot \frac{h\left(P_{diffuser\_outlet}, s_{suction\ nozzle\_inlet}\right) - h_{suction\ nozzle\_inlet}}{h_{motive\ nozzle\_inlet} - h\left(P_{diffuser\_outlet}, s_{motive\ nozzle\_inlet}\right)} \quad (4)$$

It was found that the efficiency of R744 ejectors available in the literature is usually between 0.2 and 0.3, whereas the efficiency associated with both R410A and R134a ejectors is generally below 0.2 [12].

A solitary constant-geometry ejector cannot ensure an effective control of the heat rejection pressure and, simultaneously, implement expansion work recovery accurately [15]. In order to overcome such a drawback, the multi-ejector concept was formulated. As schematized in Figure 2, this relies on a block hosting several fixed geometry ejector cartridges of various size and arranged in parallel. The multi-ejector modules available on the market feature of 4–6 vapor ejectors and, as regards food retail applications, 2 liquid ejectors. At least one of the vapor ejectors is in operation and the necessary capacity is constantly fulfilled by changing their combination, besides guarantying the occurrence of the optimal high-side working conditions in any operating mode. Therefore, the mass flow rate required to meet the cooling load is available in any running mode, permitting to handle the variable demands appropriately. The scenario involving the use of 3 out of 6 ejectors is represented in Figure 2. Solenoid valves employed for activating the ejectors are located on the upper part of the block (Figure 2), while the pressure level can be measured by using the pressure sensors (located on the right-hand side in Figure 2) for each port (i.e., high pressure side, suction and discharge ports, located from the top to the bottom on the left-hand side in Figure 2). Typically, an expansion valve is arranged in parallel with the multi-ejector block to unceasingly and effectively control the gas cooler pressure to the detriment of some of the available expansion work recovery.

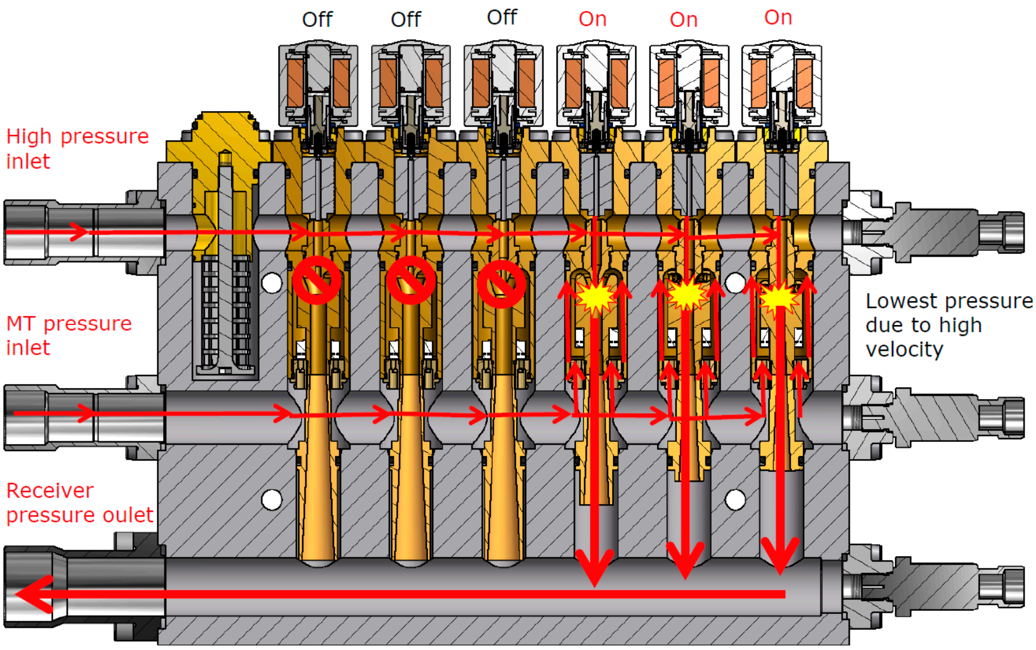


**Figure 2.** Sketch of the multi-ejector block [16].

As for supermarket refrigeration units, additional energy savings are obtained by overfeeding the evaporators. As a consequence, these heat exchangers can operate at a higher working temperature than conventional dry-expansion evaporators. Ejectors have been successfully implemented as a simple way to recirculate liquid out of the evaporators. It is worth remarking that evaporator overfeeding, in which excess liquid recirculation is provided by a liquid ejector with an efficiency of 8%, improves the overall annual performance by 15%, whereas a vapor ejector with a peak efficiency of 30% would lead to an annual performance enhancement by 5%, depending on the outdoor temperature profile [17].

## 3. Supermarket Applications

The multi-ejector concept was firstly applied to commercial refrigeration systems due to their major negative environmental impact. This is mainly caused by their significant high electricity consumptions as well as their relevant refrigerant charge losses. As an example, it was estimated that a typical American food retail store having a sale area of about 3700÷5600 $m^2$ consumes approximately 2÷3 GWh of electricity yearly [18]. Furthermore, the average annual leakage rate of the working fluid is roughly between 3% and 22% of the total charge [19] and R404A ($GWP_{100\ years}$ =

3943 $kg_{CO_{2,equ}} \cdot kg^{-1}_{refrigerant}$ according to AR5) is the most widely employed refrigerant in the European food retail industry [19].

### *3.1. Evolution of System Layout*

In the last 10 years "$CO_2$ only" supermarket refrigeration system layouts have experienced a considerable evolution, leading these solutions to move from the 1st to the 3rd generation. This significant technological development has targeted an enhancement in their energy efficiency in any climate context, with particular emphasis on the units located in warm locations.

The term "1st generation" refers to the basic R744 booster supermarket refrigeration plant layout including the flash gas by-pass valve (schematic on the left-hand side in Figure 3) [20,21]. Currently such a solution presents on the high pressure (HP) side one or two de-superheater(s) devoted to heat recovery for space heating and DHW purposes and located upstream of the air-cooled gas cooler/condenser [22]. Therefore, R744 coming out of the latter heat exchanger is throttled to the IP, leading to the generation of a liquid/vapor mixture. The liquid fraction, being separated in the IP liquid receiver, is employed for feeding the medium (MT) and low temperature (LT) evaporators. The refrigerant exiting the LT evaporators is then drawn by the "booster" (i.e., LT) compressors and compressed to the medium pressure (MP). The pressure of the vapor in the IP liquid receiver is reduced to MP via flash gas by-pass valve, which is then mixed with the refrigerant coming out of both the MT evaporators and LT compressors, before being compressed by the MT compressors to HP. Many investigations on this solution (e.g., [5,23,24]) are currently available in the open literature. These systems are very popular in Northern Europe (i.e., cold areas), as they perform similarly to or better than a conventional HFC-based unit at outdoor temperatures up to about 24 °C [25].

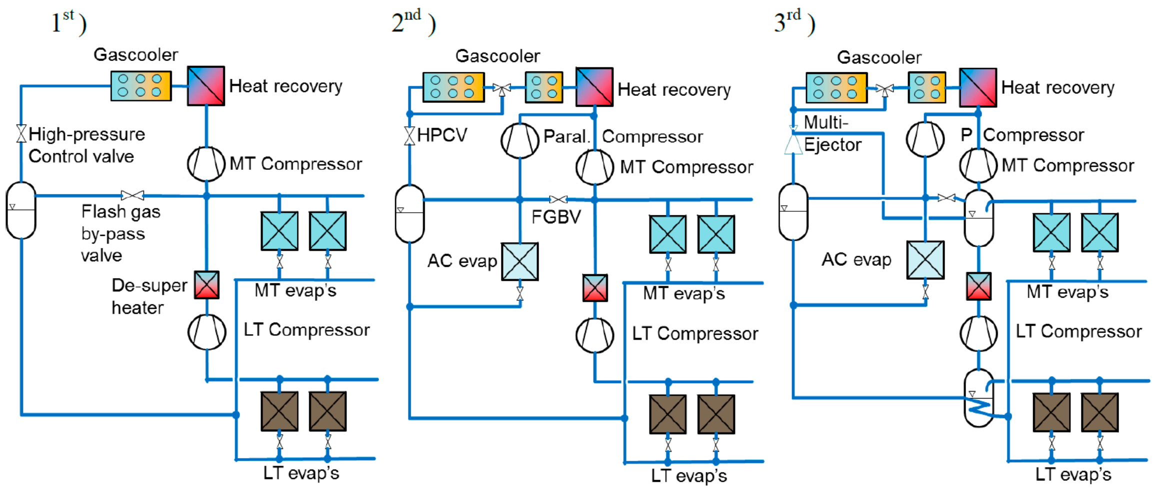


**Figure 3.** Schematic of the 1st, 2nd and 3rd generation of "$CO_2$ only" booster supermarket refrigeration system layouts [20].

A first step towards the adoption of such HFC-free solutions in warm areas is offered by the 2nd generation [20,21], i.e., parallel compression-equipped units (schematic on the middle in Figure 3). The adoption of parallel (or auxiliary) compression permits MT compressors to be unloaded for the sake of use of auxiliary compressors, which perform at a higher suction pressure (and thus at more favorable operating conditions) than the former. As a consequence, energy savings can be achieved compared to the 1st generation. The investigation by Karampour and Sawalha [26], based on some filed measurements, recently revealed that parallel compression offers high energy savings in cold climates, while it is not fully suitable for hot climates. Parallel compression-based R744 systems have been widely studied by many researchers (e.g., [27–29]).

The proliferation of transcritical R744 refrigeration plants in the commercial sector is thus expected to occur with the aid of the concurrent implementation of several energy efficient measures [8], such as parallel compression, overfed evaporators [30,31] and multi-ejector concept, i.e., via the 3rd generation of "$CO_2$ only" supermarket refrigerating systems (schematic on the right-hand side in Figure 3) [20,21]. Therefore, the expansion work is partially recovered and used by the vapor ejectors for moving part of the refrigerant after MT evaporators to the parallel compressors, which operate at a higher suction pressures and thus leading to considerable energy savings, especially at severly high outdoor temperatures.

The unique properties of $CO_2$ favor the effective recover of heat for space heating and DHW purposes [22,32]. This permits these HFC-free solutions to additionally increase their energy saving [22,33] and reduce their carbon footprint [34], besides offering satisfactory payback times [35]. The waste heat utilisation process, which has become an integral part of any "$CO_2$ only" supermarket refrigeration plant, further promotes the use of a multi-ejector block as transcritical operating conditions commonly take place in heating mode [22].

### *3.2. Evolution of Multi-Ejector Equipped System Layout*

The first proposed R744 multi-ejector enhanced parallel compression system architecture, allowing the overfeeding of MT evaporators, is sketched in Figure 4. Additionally, Minetto et al. [36] recommended the adoption of an internal heat exchanger (IHX) as presented in Figure 5 to overfeed the LT evaporators too. The additional energy benefits derived from adopting such a measure has led the system layout (and similar system architectures) to become the preferred solutions on the part of the end-users as multi-ejector based units are chosen. However, as the LT evaporators are overfed, the presence of a low pressure (LP) accumulator to trap the liquid before compressors is mandatory, since liquid cannot possibly evaporate in the heat exchanger indicated as IHX D in Figure 5 [37]. Furthermore, IHX C (Figure 5) aims at heating up the refrigerant before this is drawn by the LS compressors in any operating conditions.

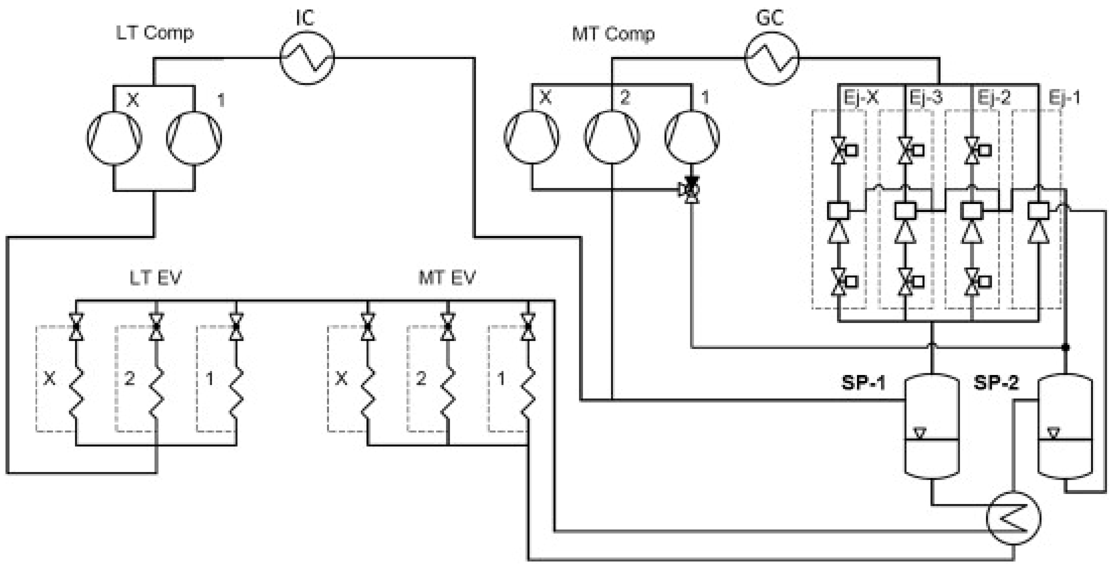


**Figure 4.** Schematic of a transcritical R744 booster supermarket refrigeration system outfitted with multi-ejector module and having MT overfed evaporators [10].

Fully-integrated (or all-in-one) solutions are tailor-made units, which successfully provide the entire refrigeration, air conditioning (AC) and DHW reclaims, alongside satisfying most of or even the whole space heating load of the selected supermarket [21,26,38,39]. According to [6], all-in-one transcritical $CO_2$ supermarket refrigeration plants equipped with multi-ejector block (e.g., schematic on the right-hand side in Figure 3) are thought to significantly bring the total investment, maintenance and running costs down, besides offering other advantages [26], such as compactness, reduction in complexity of communication between all the entities responsible for operating the various units. Also, the adoption of these units permits overcoming the persisting problem represented by the selection of the best refrigerant for AC and heating applications. The system layout schematized in Figure 6 and adopted in a supermarket in the North of Italy simultaneously implements both the all-in-one and multi-ejector concept [21].

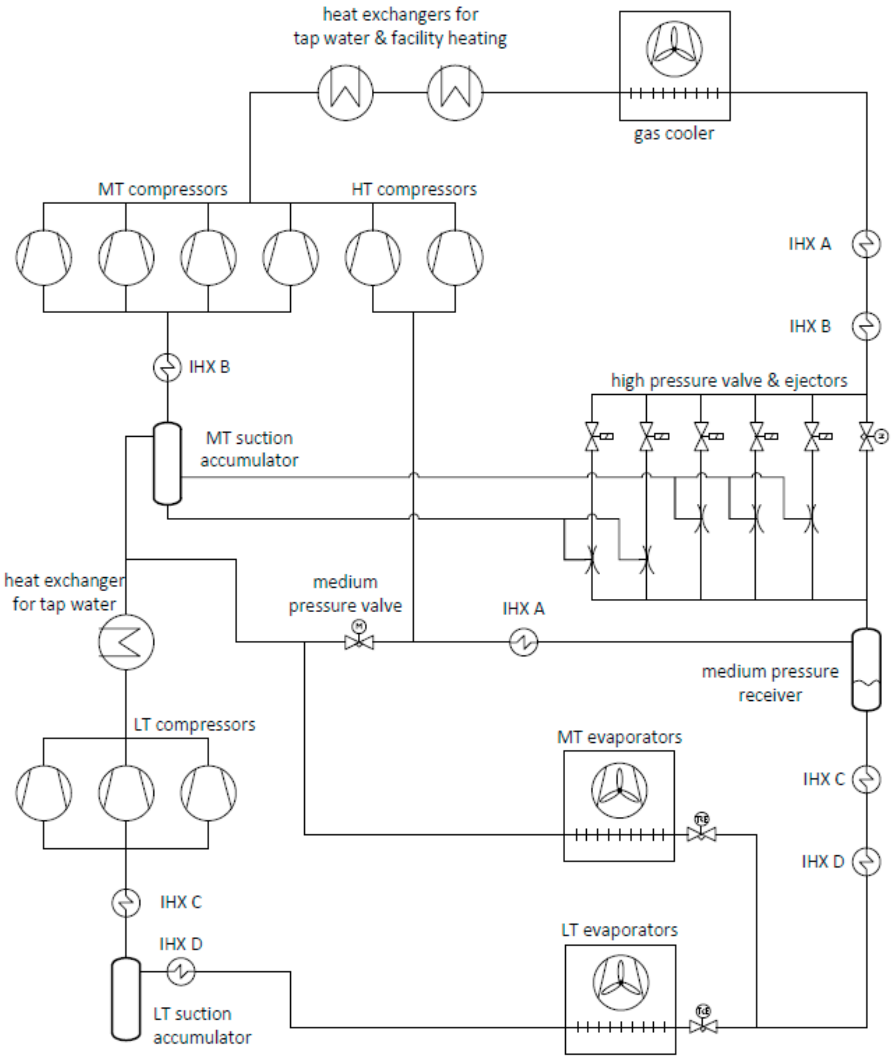


**Figure 5.** Schematic of a transcritical R744 booster supermarket refrigeration system outfitted with multi-ejector module and having both MT and LT overfed evaporators [37].

Hafner [39] predicted that next generation of commercial "$CO_2$ only" refrigerating systems will be characterized by both the application of the all-in-one concept and the use of two multi-ejector modules (i.e., one dedicated to refrigeration loads and the other to AC purposes).

The unit architecture sketched in Figure 7 represents a suitable solution for supermarkets located in Southern Europe or Middle East [40]. The solution features: (1) the presence of two multi-ejectors modules (i.e., one dedicated to refrigeration loads and the other to AC purposes); (2) the implementation of the "principle of pivoting" (see Section 3.4.1); (3) the use of MT and LT overfed evaporators; (4) an exterior heat exchanger (HX) operating as an additional evaporator to increase the amount of recoverable heat in wintertime and as a gas cooler in AC mode; (5) an auxiliary heat sink upstream of the multi-ejector blocks to cool R744 down and (6) the integration of ice-water cooling evaporators coupled with the AC multi-ejector block to increase the suction pressure of the parallel compressors.

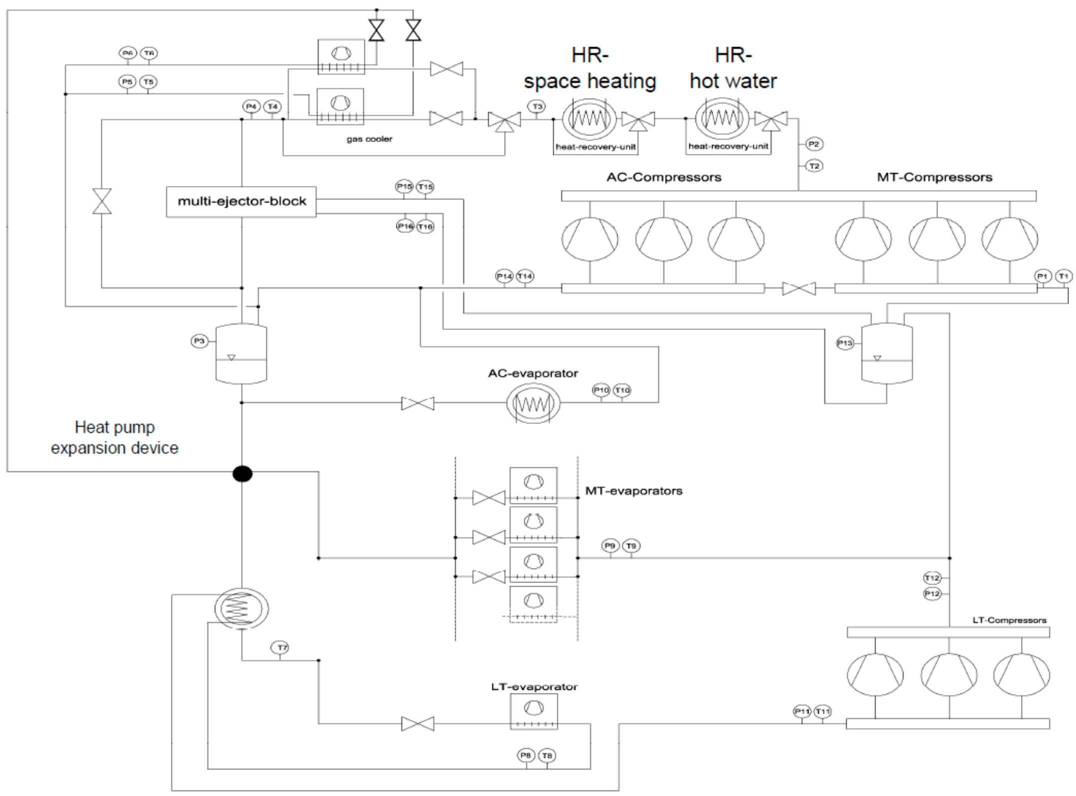


**Figure 6.** Fully-integrated R744 multi-ejector enhanced parallel compression system installed in a food retail store located in Spiazzo (Northern Italy) [21].

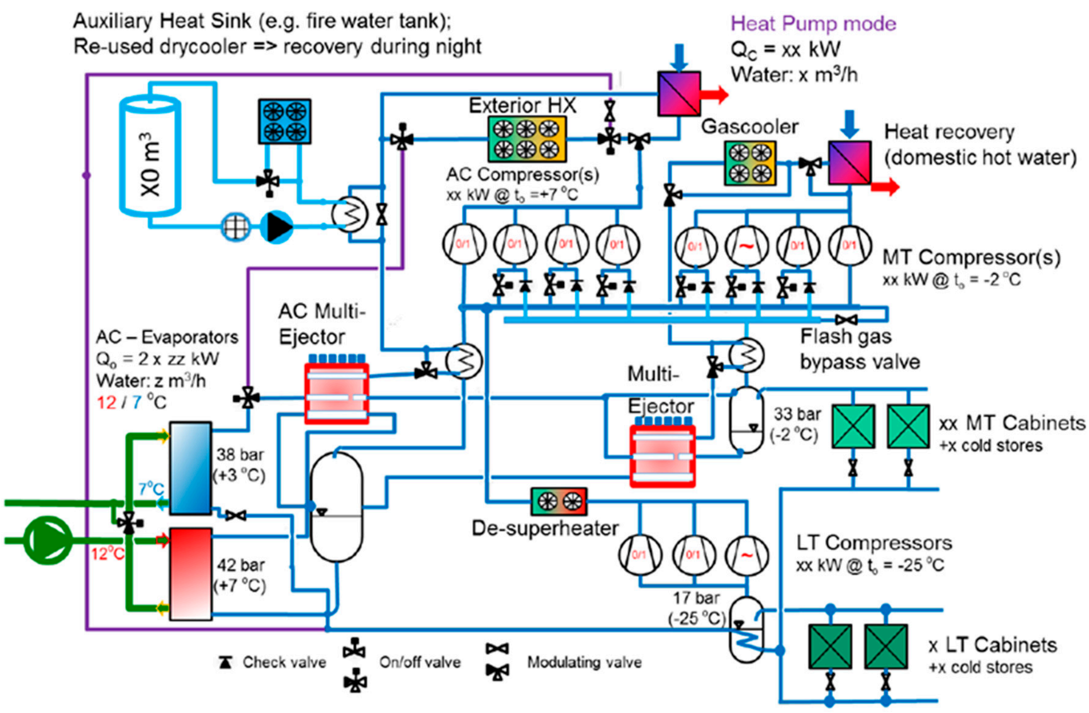


**Figure 7.** Fully-integrated R744 multi-ejector enhanced parallel compression system suitable for supermarkets located in warm areas [40].

The adoption of a secondary fluid between the refrigeration plant and the AC/heating unit introduces additional penalizations [40,41]. These can be avoided thanks to the favorable thermo-physical properties of R744, which can be employed in direct cooling and heating fan coils and air curtains installed inside the building. The implementation of such a technique would lead to many benefits, such as higher energy efficiency, reduction in number of components, possible decrease in investment costs, no corrosiveness issues. A refrigeration plant layout based on this concept is presented in Figure 8. In AC mode, the expansion valves upstream of the fan coils and air curtains, operating as evaporators, guarantee the correct amount of R744 to each unit. As the heating mode takes place, the gas cooler is by-passed and thus the heat is directly transferred into the building by the fan coils and air curtains.

The solution presented in Figure 9 enables recovering part of the available expansion work as the AC operations take place as well. The appropriate amount of $CO_2$ in the fan coil or air curtain is obtained via the modulating 3-way-valve located 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).

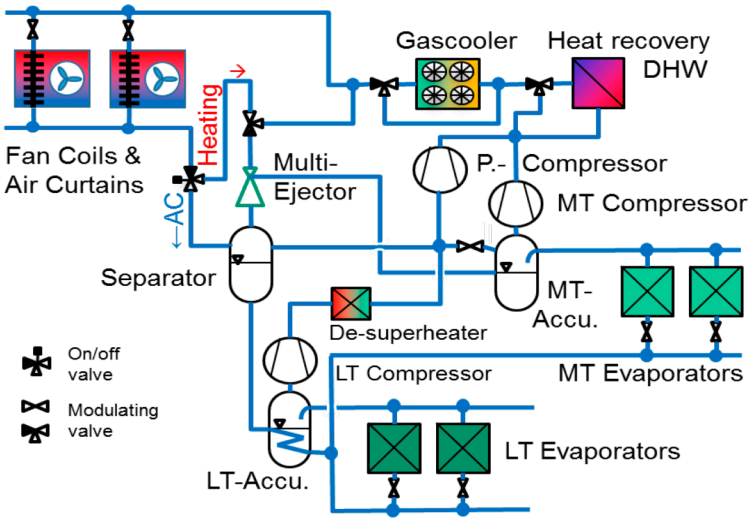


**Figure 8.** Integration of direct heating and cooling fan coils and air curtains in a transcritical R744 supermarket refrigeration system (multi-ejector block partly by-passed in AC mode) [40].

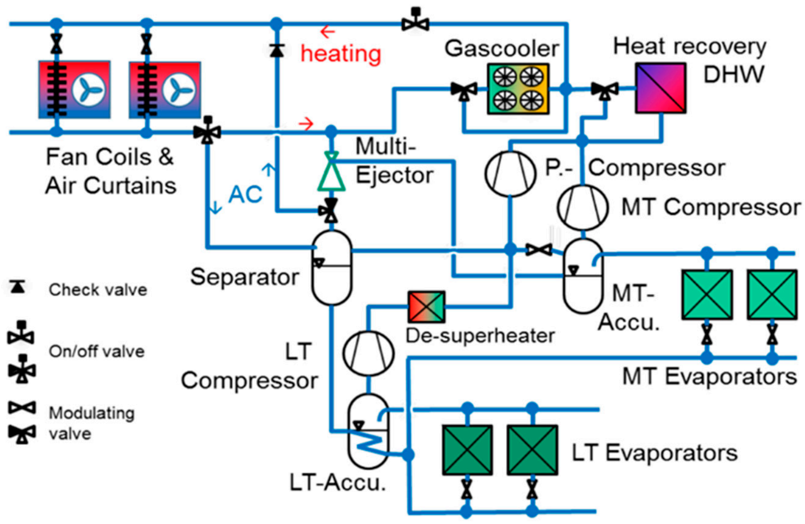


**Figure 9.** Integration of direct heating and cooling fan coils and air curtains in a transcritical R744 supermarket refrigeration system (ejectors employed in AC mode as well) [40].

### *3.3. Multi-Ejector Based Solutions without Integration with Air Conditioning Unit*

#### 3.3.1. Technological Aspects

The use of R744 ejectors requires technological assessments under multiple aspects. The first challenge is related to the ability of the multi-ejector module to provide HP control and optimization under variable operating conditions.

The experimental results presented in [15] suggested that the heat rejection pressure can be satisfactorily controlled by a multi-ejector block in commercial refrigeration applications. As showed in Figure 10, in fact, the researchers evaluated similar profiles of the discharge 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 module.

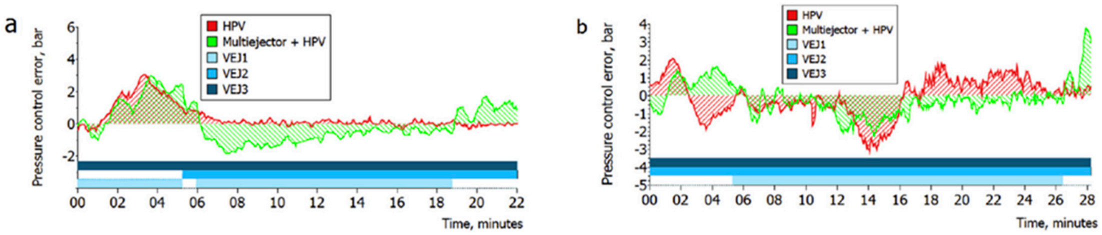


**Figure 10.** Deviation between the actual value and set-point value for the heat rejection related to a rapid change in load (**a**) and in outdoor temperature (**b**) [15].

The field measurements gathered in [42,43] revealed that a multi-ejector module can successfully switch the gas cooler/condenser from floating condensing to heat recovery mode and vice versa (as showed in Figure 11 after 13:00) as well as the MT evaporators from superheated to overfed mode and vice versa. In the reference example, the authors also found that the minimum number of ejectors needed to reach the discharge pressure set points without too many on/off switches of these devices was 3. Finally, they demonstrated that the control system can suitably handle possible blockages of an ejector nozzle.

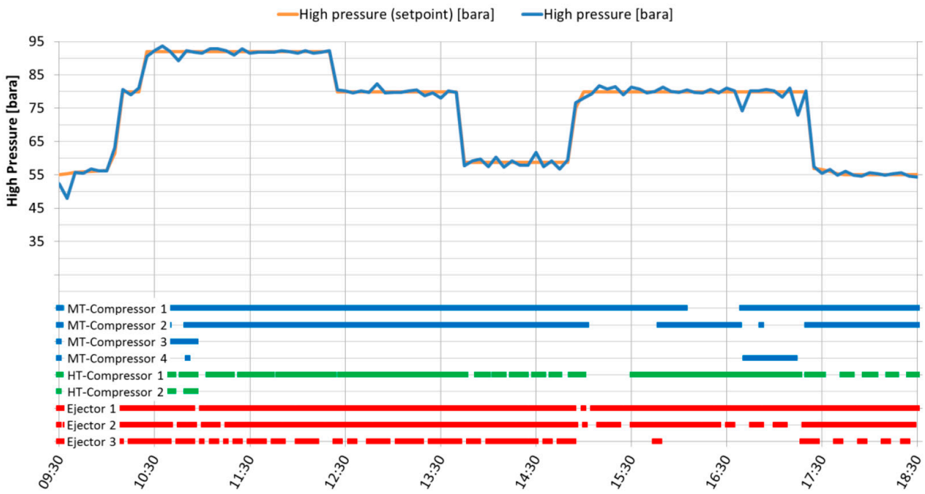


**Figure 11.** Operating conditions aimed at demonstrating the successful switching from floating condensing to heat recovery mode and vice versa via multi-ejector concept [42].

Also the oil management can be properly performed, taking care of recovery both at compressor discharge and from the liquid separator [15,21].

The significant use of the parallel compressors [21,37] allows reductions in their maintenance issues all over the year compared to the conventional booster configuration [44].

According to [45], the use of the multi-ejector module can successfully bring down the installed displacement of compressors. Furthermore, [17] highlighted that the implementation of the multi-ejector concept allows:

- Significantly decreasing the compressor discharge temperature. This is shown in Figure 12, in which curve refers to the typical operating conditions of an overfed evaporator, whereas curve b and c are related to two conventional running modes of dry-expansion evaporators. Therefore, these results highlight considerable benefits to the lifetime of the lubricant, components on the discharge line and de-superheater for heat recovery;
- Improved protection against liquid in the compressor suction manifolds thanks to both the adopted active methods with the purpose of limiting the liquid level and the MP liquid receiver;
- A reduction in total installed swept volume in relation to a single compression system;
- An enhanced overall energy efficiency at outdoor temperatures up to between 40 °C and 42 °C.

| Curve | Suction pressure Saturated press. [°C] | Suction temperature [°C] |
|---|---|---|
| A | -3 | +2 |
| B | -8 | 20 |
| C | -8 | 25 |

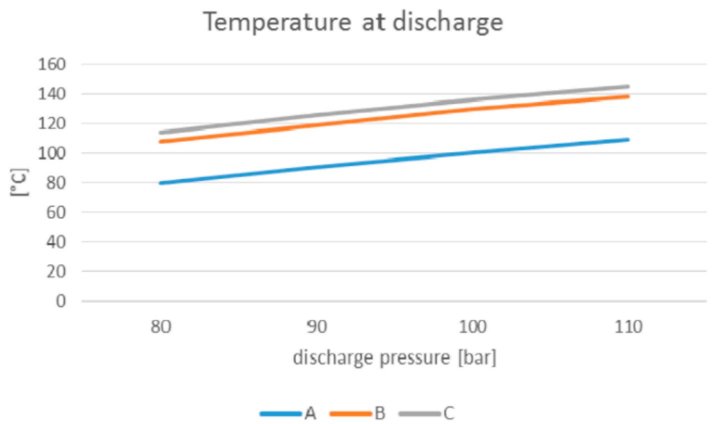


**Figure 12.** Effect of the heat rejection pressure on the compressor discharge temperature for the 3 investigated scenarios [17].

The experimental study in [46] demonstrated that a multi-ejector block leads to efficient and stable performance over the whole range of the investigated operating regime for commercial refrigeration applications.

3.3.2. Theoretical Assessments/Statements

Hafner et al. [9] estimated that a R744 multi-ejector enhanced parallel compression solution (same as that in Figure 4) in a food retail store located in Mediterranean Europe enables an energy saving by approximately 11% over a conventional booster system.

The dynamic simulations implemented by Hafner at al. [10] (same solution as that in Figure 4) showed that typical Coefficient of Performance (*COP*) increments in the refrigeration mode by 17% in Athens (Greece), 16% in Frankfurt (Germany) and 5% in Trondheim (Norway) can be achieved in summertime, while the ones associated with wintertime were found to be from 20% to 30% over a conventional booster plant.

The results obtained by Minetto et al. [44] brought to light that the adoption of the multi-ejector concept leads to an energy reduction by 22.5% compared to a basic "$CO_2$ only" unit for a MT commercial refrigeration application operating in Bari (Southern Italy).

Pisano [47] stated that a food retail store located in Bari can decrease its energy consumption by almost 30% by replacing a conventional booster unit with a multi-ejector based booster solution (similar to that in Figure 4) (Figure 13).

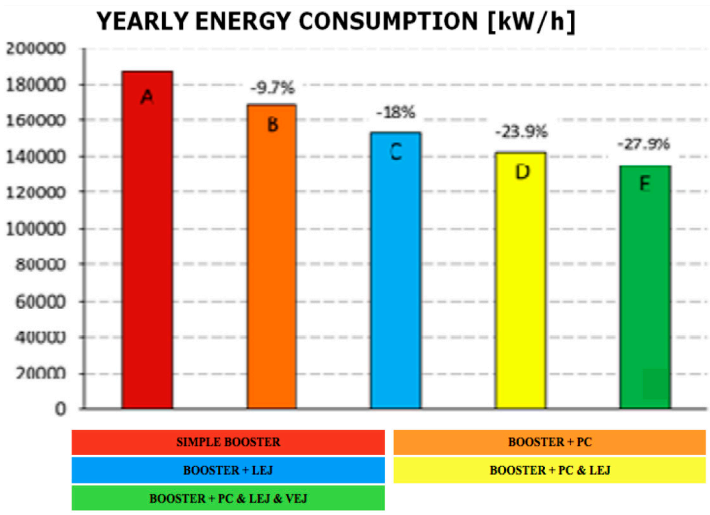


**Figure 13.** Energy savings of various transcritical R744 booster supermarket refrigeration systems compared to a conventional transcritical R744 booster supermarket refrigeration plant in Southern Italy [47].

Schönenberger [37] claimed that, compared to the solution with parallel compression, an energy saving between 15% and 25% can be accomplished with the aid of the multi-ejector concept (same system as that in Figure 5), depending on the heat demand, application and climate conditions.

The assessment by Gullo et al. [48] revealed that R744 ejector supported parallel vapor compression systems (similar to those in Figures 4 and 5) reduce the energy consumption from roughly 20% to 27% in comparison with a R404A unit in an average-size food retail store located in Mediterranean Europe. At the same boundary conditions, parallel compression offers, at best, an energy conservation by 6.4%.

Gullo et al. [49] estimated that R744 multi-ejector enhanced parallel compression units (similar to those in Figures 4 and 5) offer energy savings between 17.8% (in Oslo, Norway) and 26.7% (in Athens) in relation to a conventional booster system and between 16.9% (in London, UK) and 23.4% (in Oslo) over a parallel compression-based solution. In comparison with a R404A unit, the adoption of the multi-ejector concept leads to a decrease in annual electricity intake from 24.6% (in Athens) to 37.1% (in Oslo).

Due to the EU F-Gas Regulation 517/2014 the adoption of R404A-based supermarket systems will not be allowed after 2022. Consequently, cascade/indirect loop arrangements are drawing interest, especially in warm locations. However, these are expected to be less efficient, as suggested in a recent report by the European Commission [50] and recently confirmed in [51,52].

Gullo and Hafner [51] carried out an investigation based on the operating conditions of a typical supermarket and several American cities, including cold, moderate and warm weathers. The results obtained showed that R744 multi-ejector enhanced parallel compression systems (similar to those in Figures 4 and 5) offer energy conservations from 17.3% to 37.8% compared to a R404A-based unit. Furthermore, energy savings up to 26% were estimated for these solutions in warm locations. At best, R1234ze(E)/R744 indirect arrangements consumed 10.5% less electricity over the R404A-based unit at the same boundary conditions.

The results of the study by Gullo et al. [52], which was based on an average-size supermarket located in several cities positioned below the so-called "$CO_2$ equator" (average yearly temperature between 14.1 °C and 18.9 °C), suggested that compared to R404A direct expansion units:

- Multi-ejector based solutions (similar to those in Figures 4 and 5) can reduce the energy consumption from 18.6% to 28.6%;
- The r1234ze(E)/R744 indirect arrangement with MT and LT flooded evaporators and the r134a/R744 cascade solution present some modest energy savings;
- The other evaluated systems (i.e., R1234ze(E)/R744 indirect arrangement with MT flooded evaporators, R290/R744 indirect arrangement with and without LT flooded evaporators, R450A/R744 cascade solution and R513A/R744 cascade system) are not suitable candidates.

Figure 14 summarizes the outcomes of the previous investigation in terms of reduction in Total Equivalent Warming Impact (TEWI) relying on R404A direct expansion units as the baseline. The authors [52] found that the adoption of the multi-ejector concept allows reducing the environmental impact from 50.7% to 90.6%, while the aforementioned R1234ze(E)/R744 indirect unit and the R134a/R744 cascade arrangement decrease the carbon footprint from 39.1% to 87.7% and from 28.8% to 65.8% TEWI, respectively.

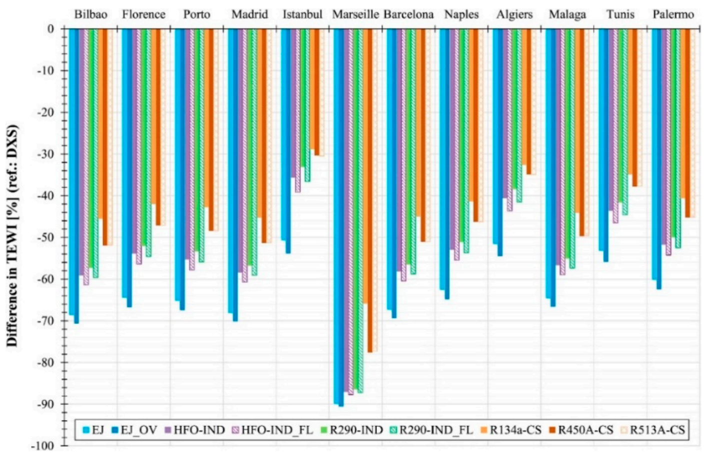


**Figure 14.** Difference in TEWI among various supermarket refrigeration solutions (DXS: R404A unit; EJ: multi-ejector based system with MT overfed evaporators; EJ_OV: multi-ejector based system with MT and LT overfed evaporators; -IND: indirect arrangements with MT flooded evaporators; -IND_FL: indirect arrangements with MT and LT flooded evaporators; -CS: cascade arrangements) in several locations positioned below the $CO_2$ equator ($t_{MT}$ = −4/−10 °C, $t_{LT}$ = −27/−35 °C, $\dot{Q}_{MT}$ = 120 kW, $\dot{Q}_{LT}$ = 25 kW) [52].

Madsen and Kriezi [53] recently showed that the implementation of the multi-ejector concept (solution similar to that in Figure 4) leads to energy savings from 13% to 29% compared to the conventional booster unit in locations featuring an average annual temperature between 0 °C and 30 °C (Figure 15).

| | Energy saving compared to Booster CO2 system | | | | | | |
|---|---|---|---|---|---|---|---|
| | | HP ejectors | LP ejectors | Flooded Operation | | | |
| Average Annual temp [C] | Parallel compression | Parallel comp. + HP ejectors | Booster sys + LP Ejector | Booster sys. with Liquid ejector | Parallel comp. sys . with liquid ejector | LP Ejector system with Liquid ejectors | HP ejector system with Liquid ejectors |
| 0 | 5% | 6% | 2% | 10% | 15% | 13% | 17% |
| 5 | 5% | 7% | 3% | 10% | 16% | 14% | 18% |
| 10 | 6% | 9% | 5% | 10% | 16% | 16% | 20% |
| 15 | 7% | 12% | 9% | 10% | 17% | 19% | 23% |
| 20 | 7% | 15% | 13% | 10% | 18% | 24% | 27% |
| 25 | 8% | 17% | 15% | 10% | 18% | 26% | 29% |
| 30 | 6% | 16% | 15% | 10% | 17% | 27% | 27% |

**Figure 15.** Energy saving of various transcritical R744 booster supermarket refrigeration systems at different average annual temperatures compared to a conventional transcritical R744 booster supermarket unit [53].

Also, LP and HP in Figure 15 respectively refer to vapor ejectors with low and high pressure lift. At the same boundary conditions, parallel compression offers reductions in energy consumption from 5% to 8%.

Gullo et al. [54] concluded that the adoption of multi-ejector based solutions is also suggested as a result of the application of the advanced exergy analysis. Such an assessment is widely recognized as the most powerful thermodynamic tool to suitably assess the performance of any energy system. In addition, the researchers found that the implementation of the multi-ejector concept leads a conventional booster unit to a decrease by about 39% in total irreversibilities at the outdoor temperature of 40 °C. This outcome was a consequence of: (i) a reduction by approximately 36% in avoidable irreversibilities taking place in the gas cooler; (ii) a decrement by about 39% in avoidable inefficiencies occurring in the compressors discharging to the heat rejection pressure; (iii) a halving of the avoidable exergy destruction related to the MT evaporators; (iv) a decrease by about 40% in total inefficiencies associated with the main expansion device.

### 3.3.3. Laboratory and Field Experimental Assessments

#### Laboratory Experimental Assessments

The experimental assessment fulfilled in [13] revealed that efficiencies of an individual ejector hosted in a multi-ejector block up to 0.3 can be measured with respect to the heat rejection pressure and temperature, the pressure lift and the evaporation pressure.

The in-depth experimental investigation in [15] brought to light that the ejector efficiencies above 0.3 can be accomplished over a broad range of the investigated operation conditions. Furthermore, the results obtained revealed that the assessed ejector efficiencies were higher than those previously gathered. However, the overall multi-ejector efficiency is gradually penalized as the expanded mass flow rate grows owing to the increasing stream irreversibilities (e.g., imperfect mixing of individual flows exiting the ejectors), although the recorded values of efficiency were found to be above 0.2. The researchers mapped the motive nozzle mass flow rate depending on the inlet density and inlet pressure (Figure 16a). In addition, it was seen that the optimum running modes of an ejector having a given geometry can be attained by varying the suction pressure ratio with respect to the gas cooler outlet conditions (Figure 16b). Furthermore, [15] discovered that the compressor efficiency has a considerable influence on the overall system efficiency with respect to the selected combination of ejector cartridges. Additionally, a maximum *COP* enhancement of 9.8% was evaluated as only 50% of the total mass flow rate went through the ejectors and the compressor was operating at the highest efficiency.

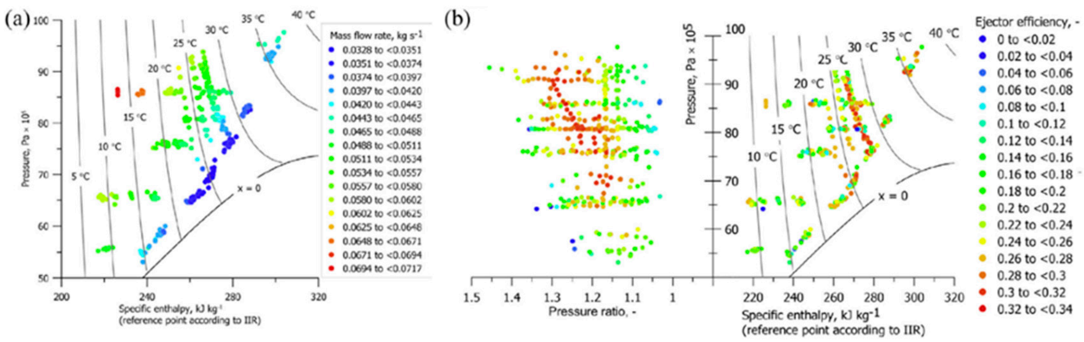


**Figure 16.** (**a**) Motive nozzle mass flow rate as a function of the motive nozzle inlet conditions for one of the investigated ejectors; (**b**) Ejector efficiency as a function of the motive nozzle inlet conditions and suction pressure ratios for one of the investigated ejectors [15].

Fredslund et al. [55] observed that vapor ejector efficiencies measured in the laboratory (Figure 17a) are comparable (and above 0.25) to those estimated from real installations operating at the typical operating conditions (i.e., $P_{lift}$ = 6 bar) (Figure 17b). According to the authors, compressor sizes (so as to satisfy the required capacity and have the parallel compressors as long as in operation), pressure lift and the oil return design should be carefully considered.

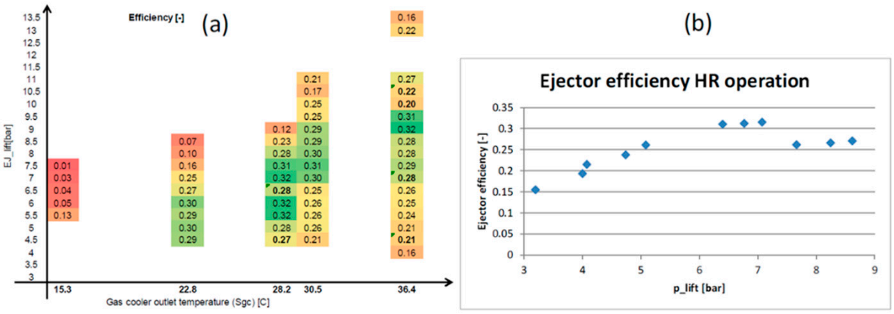


**Figure 17.** Comparison between the ejector efficiencies measured in the laboratory (**a**) and those estimated in a real application performing in heat recovery mode (**b**) [55].

Haida et al. [56] proved that the adoption of the multi-ejector block permits increasing *COP* and exergy efficiency up to 7% and 13.7% over the parallel compression-based unit, respectively. In addition, efficiencies of the multi-ejector module up to 0.33 were estimated with respect to the pressure lift and the motive and suction conditions. The researchers also pointed out that it is required to mutually taken into account the multi ejector block and the compressor rack interactions when designing the refrigeration plant.

The experimental results obtained by Pardiñas et al. [57] demonstrated that efficient MT compressors in their range of operation are compulsory to accomplish significant energy conservations (even with efficient vapor ejectors) as vapor ejectors boost parallel compressors and unload MT compressors. Thus, maintaining high compression efficiency for the MT machines even in part-load becomes a crucial factor for maximizing the system efficiency gains thanks to the ejector use.

Field Experimental Assessments

The incorporation of the multi-ejector module into a R744 booster unit enables increasing the suction pressure of the auxiliary compressors by 3÷10 bar over that of the MT compressors [43,58].

Kriezi et al. [59] suggested employing a liquid ejector designed for summer operating conditions and another for winter running modes owing to the highly fluctuating demands of food retail applications. Ejectors aimed at vapor removal can adequately pump some liquid in summertime.

The field data presented in [36] (Figure 18) demonstrated that an increment in MT by 6 K compared to a dry-expansion evaporator can be attained with the aid of the multi-ejector concept. The increase in LT by 8 K presented in Figure 18 was a result of the adoption of an IHX, as mentioned above. Both achievements can be maintained all over the year, leading to reductions in frost formation and number of defrost cycles in relation to conventional technology [17,37,42,43].

Kriezi et al. [60] estimated the energy benefits associated with the adoption of MT overfed evaporators on the part of a multi-ejector based system (similar to that in Figure 4) with the aid of field measurements collected between June and August 2017. The authors estimated that MT can be increased on average by 4.5 K, as dry-expansion evaporators with a minimum degree of superheating of 6 K perform in overfed mode, with a minimum degree of superheating set to 1 K. As a consequence, the total *COP* values can be enhanced on average by about 5% over the investigated range of running modes (Figure 19a), leading to a potential decrease in power input of approximately 4.5% (Figure 19b).

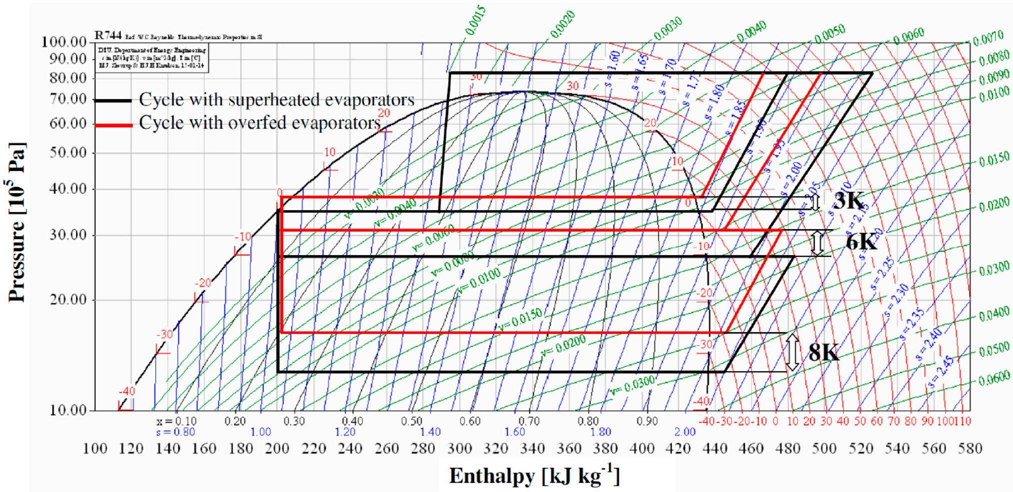


**Figure 18.** Comparison between the thermodynamic cycle with superheated evaporators and that with overfed evaporators [17].

**(a)**

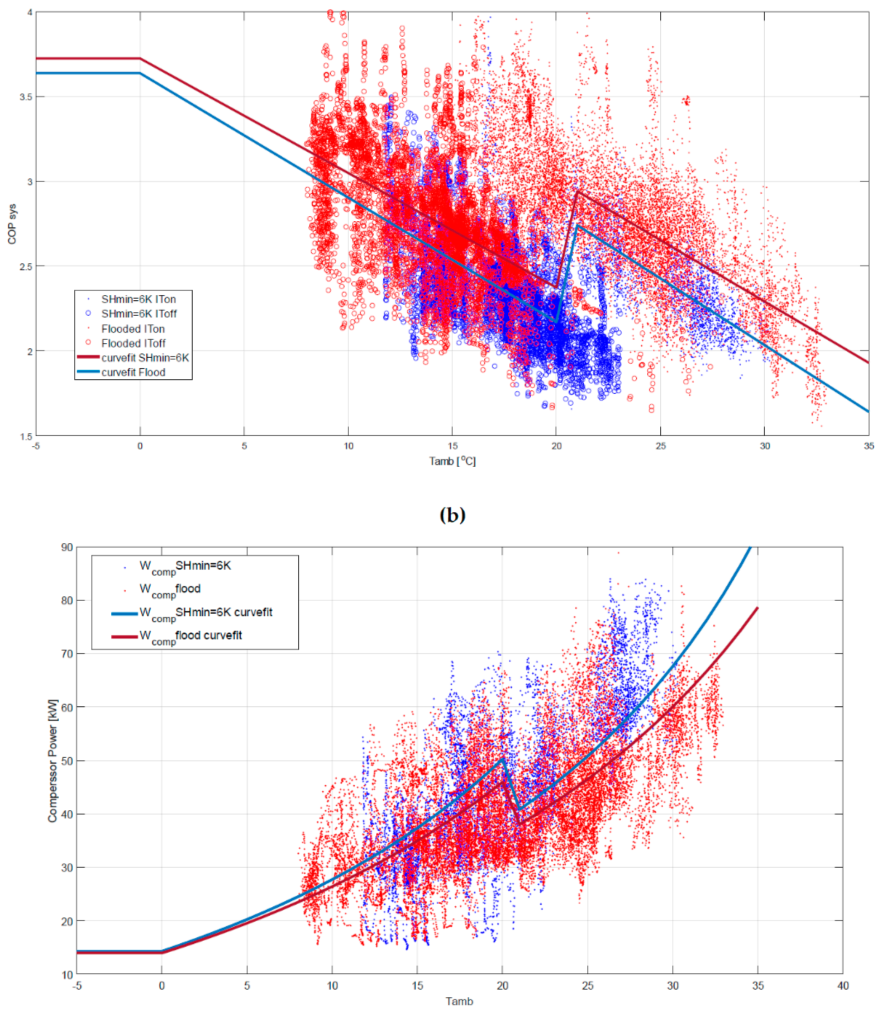


**Figure 19.** Comparison of total *COP* values (**a**) and total compressor power input (kW) (**b**) between the investigated system using MT dry-expansion evaporators with a minimum degree of superheating of 6 K (blue line) and the same system relying on MT flooded evaporators with a minimum degree of superheating set to 1 K (red line) [60].

The *COP* increase and the compressor power reduction were lower than expected, as the system had a high LT load (equivalent to MT capacity) and the LT evaporators were running in dry-expansion mode. However, the authors also highlighted that the energy advantages related to the parallel compressor were underestimated as well as the ones associated with the potential reduction in number of defrost cycles were not considered.

Schönenberger et al. [42] and Hafner et al. [43] demonstrated that energy savings by 10% in comparison with the solution using parallel compression and by 18% over a conventional booster system can be obtained in a supermarket (system similar to that in Figure 4) located in the region of Fribourg (Switzerland) in wintertime, respectively.

The energy consumption of the first installation relying on the multi-ejector concept (similar to that in Figure 4) is compared to that of three similar units employing parallel compression in Figure 20. It was found to offer an energy conservation by 14% over the same period of time in the Swiss climate context [42].

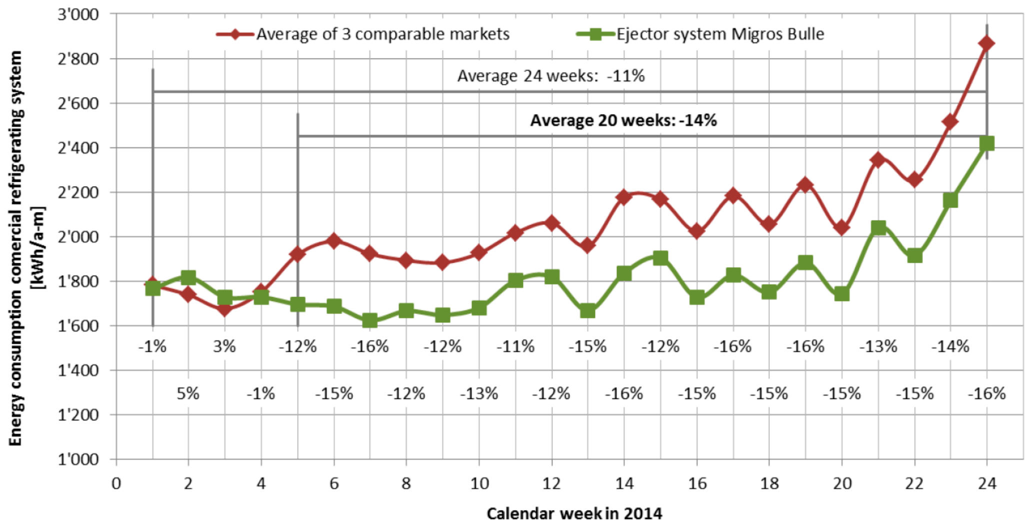


**Figure 20.** Energy consumption comparison between the first unit implementing the multi-ejector concept and three similar systems relying on parallel compression in the Swiss climate context [42].

### 3.3.4. Economic Assessments

As presented in Figure 21, the addition of vapor ejectors with high pressure lift to units relying on parallel compression is economically acceptable for supermarkets with cooling capacities over 75 kW and located in cities having an average annual temperature above 15 °C [60]. LP and HP in Figure 21 respectively indicate vapor ejectors with low and high pressure lift.

| | Pay Back Liquid ejector [years] | | | | Pay Back HP ejector solution [years] | | | Pay Back LP ejector solution [years] | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Average annual temperature [ºC] | Booster + Liq VS Booster 40 kW | Booster + Liq VS Booster 75 kW | Booster + Liq VS Booster 150 kW | Booster + Liq VS Booster 300 kW | HP Ejector VS parallel 75 kW | HP Ejector VS parallel 150 kW | HP ejector VS parallel 300 kW | LP ejector VS Booster 40 kW | LP ejector VS Booster 75 kW | LP ejector VS Booster 150 kW |
| 0 | 3.70 | 1.97 | 1.58 | 0.89 | 14.96 | 13.37 | 12.51 | 21.53 | 17.74 | 18.74 |
| 5 | 3.50 | 1.87 | 1.49 | 0.84 | 9.50 | 8.50 | 7.96 | 13.59 | 11.20 | 11.83 |
| 10 | 3.17 | 1.69 | 1.35 | 0.76 | 5.70 | 5.08 | 4.75 | 8.37 | 6.89 | 7.28 |
| 15 | 2.61 | 1.39 | 1.11 | 0.63 | 2.63 | 2.32 | 2.16 | 4.15 | 3.42 | 3.61 |
| 20 | 2.13 | 1.14 | 0.91 | 0.51 | 1.35 | 1.18 | 1.09 | 2.34 | 1.93 | 2.04 |
| 25 | 1.79 | 0.96 | 0.76 | 0.43 | 0.87 | 0.75 | 0.69 | 1.69 | 1.39 | 1.47 |
| 30 | 1.81 | 0.97 | 0.77 | 0.43 | 0.85 | 0.73 | 0.66 | 1.69 | 1.39 | 1.47 |

**Figure 21.** Payback period for ejector addition to various transcritical R744 booster supermarket refrigeration systems with respect to both the average annual temperature and the required cooling capacity [60].

Pisano [47] recently reported that a "$CO_2$ only" booster refrigeration system equipped with multi-ejector block (similar to that in Figure 4) (green line in Figure 22) offers a return of investments of 2 years (based on capital and running costs) compared to a basic "$CO_2$ only" booster unit (red line in Figure 22) in a supermarket located in Bari.

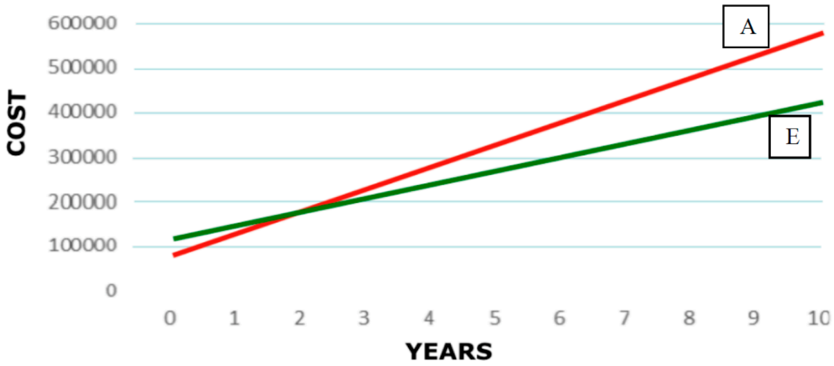


**Figure 22.** Comparison in terms of return on investments between a transcritical R744 booster refrigeration plant outfitted with multi-ejector block (green line) and a conventional transcritical R744 booster refrigerating unit (red line) in a supermarket located in Bari [47].

### *3.4. Multi-Ejector Based Solutions with Integration with Air Conditioning Unit*

#### 3.4.1. Technological Aspects

Pardiñas et al. [61] theoretically investigated the appropriate control of the heat rejection pressure as either a high ratio of AC demand to MT refrigeration load occurs or the AC ejectors operate inefficiently. The outcomes obtained suggested adopting the control technique relying on: setting the AC evaporation pressure, computing the ideal pressure lift of the AC ejectors at the selected outdoor conditions and employing it to evaluate the set point for the control of the auxiliary compressors. A decrease in this pressure lift needs to be considered as the discharge pressure control became impossible.

The adoption of the so-called "pivoting principle" for compressors was recommended in many studies [36,39,40,62]. This technique has the purpose to enable the MT and auxiliary compressors to be widely interchangeable so as to decrease the total displacement of the installed compressors. In fact, on the one hand, the total required displacement being necessary in wintertime is very low (or even zero). On the other hand, the auxiliary compressor swept volume considerably growths in summertime due to both the flash vapor generated during the expansion process and to the vapor being pre-compressed by the ejectors. The interchangeability of the MT and auxiliary compressors is implemented by linking the compressors to either the MT or the parallel suction group with the aid of on/off valves installed upstream of them (x2–x5 in Figure 23) [40], as a function of the operation conditions. Hafner [39] also claimed that this feature gives rise to a "gap-free" control of the refrigeration load, besides lowering the installation cost as well as enhancing the compactness of the unit.

According to Pardiñas et al. [62], the implementation of the "pivoting principle" favors greater system flexibility with respect to following the actual load profile (i.e., enlargement in operational range of the refrigeration plant). The researchers also highlighted that a simple and inexpensive solution, which should not influence the oil return of the compressors, to apply the aforementioned principle is potentially available. Furthermore, Pardiñas et al. [62] stated that the average annual operation time of compressors should be broadened, implying a reduction in overall ownership costs. However, the energy savings achievable through the "pivoting principle" are not noteworthy [62]. These could be increased by using the proposed pivoting technique at the discharge of the LT compressors, further promoting a growth in their number of hours in operation.

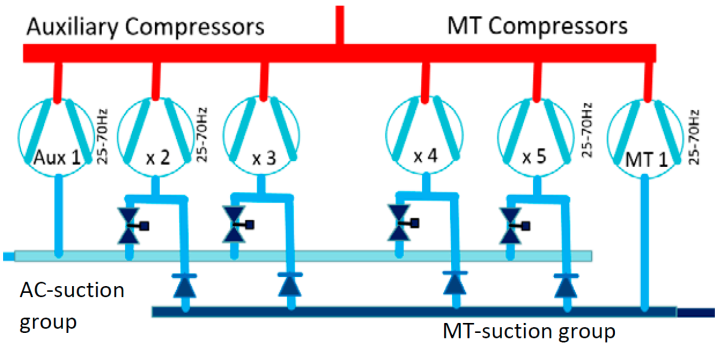


**Figure 23.** Schematic of the application of the "pivoting principle" to 4 out of 6 compressors [40].

### 3.4.2. Theoretical Assessments/Statements

Gullo et al. [48] estimated that the implementation multi-ejector concept (solutions similar to that in Figure 6) leads to energy conservations between 15.6% and 26.2% compared to conventional HFC-based units, depending on the size of both the AC equipment and the supermarket, as well as on the weather conditions.

The study by Pardiñas et al. [62] brought to light that the adoption of a (vapor) multi-ejector block is energy advantageous at outdoor temperatures above 25 °C compared to the unit relying on parallel compression (Figure 24). Further energy savings can be achieved by using an AC multi-ejector module (8.3% at 30 °C and 8.6% at 25 °C). The investigation was carried out by considering the running modes of a typical Norwegian supermarket. In addition, the authors [62] found that:

- The multi-ejector enhanced parallel compression unit with two multi-ejector blocks (one for MT load and one for AC demand) and AC evaporator located downstream of the liquid receiver is a suitable solution as high AC pressures are required;
- The multi-ejector enhanced parallel compression system with MT multi-ejector module and AC evaporator located upstream of the liquid receiver is an adequate solution as low AC pressures are necessary;
- The optimum discharge pressure is strongly related to the outdoor temperature, MT, AC evaporator position and AC evaporating pressure in transcritical operating conditions.

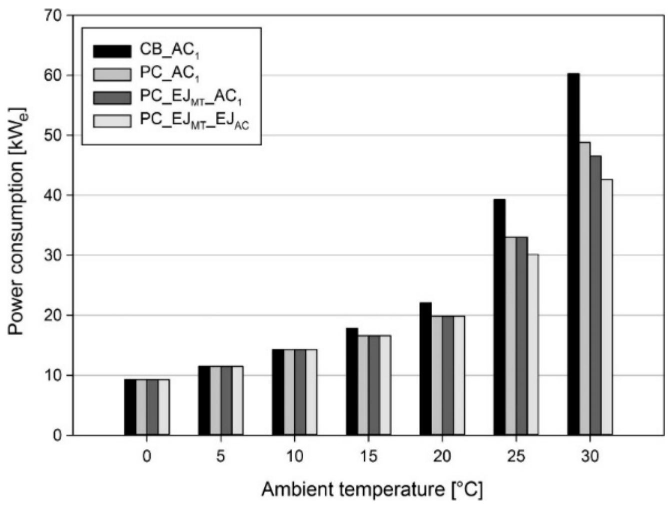


**Figure 24.** Electric power input of a conventional booster system (CB_AC), booster system with parallel compression (PC_AC), multi-ejector enhanced parallel compression system with (PC_EJ$_{MT}$_EJ$_{AC}$) and without (PC_EJ$_{MT}$_AC) AC multi-ejector module in a typical Norwegian food retail store ($p_{MT}$ = 28 bar, $p_{LT}$ = 15 bar, $p_{lift,AC}$ = 5 bar, $\dot{Q}_{MT}$ = 60 kW at $t_{outdoor}$ = 30 °C, $\dot{Q}_{LT}$ = 10 kW, $\dot{Q}_{AC}$ = 45 kW at $t_{outdoor}$ = 30 °C) [62].

Compared to R404A direct expansion units for the refrigeration loads and a R410A chiller for the AC demand, the study by Gullo et al. [52] also revealed that:

- A multi-ejector based solution integrated with the AC unit (solution similar to that in Figure 6) consumes from 19.3% to 26.9% less electricity;
- The investigated r1234ze(E)-based indirect arrangements (i.e., With and without integration with the AC equipment) offer energy savings between 4.7% and 6.4%;
- The r134a/R744 cascade system separately operating with a r1234ze(E) chiller can reduce the energy consumption from 1.9% to 4.7%;
- The other assessed solutions (i.e., R1234ze(E)-, R290-, R450A- and R513A-based systems) are not appropriate candidates.

Figure 25 summarizes the results of the aforementioned study [52] in terms of reduction in TEWI (baseline: R404A direct expansion units for refrigeration loads and a R410A chiller for AC reclaim). The researchers estimated that the implementation of the multi-ejector concept leads to a decrease in carbon footprint from 53.2% to 90.9%. Also, the aforementioned R1234ze(E)/R744 indirect solutions and R134a/R744 cascade arrangement can reduce TEWI from 40.8% to 88.5% and from 31.5% to 69.7%, respectively.

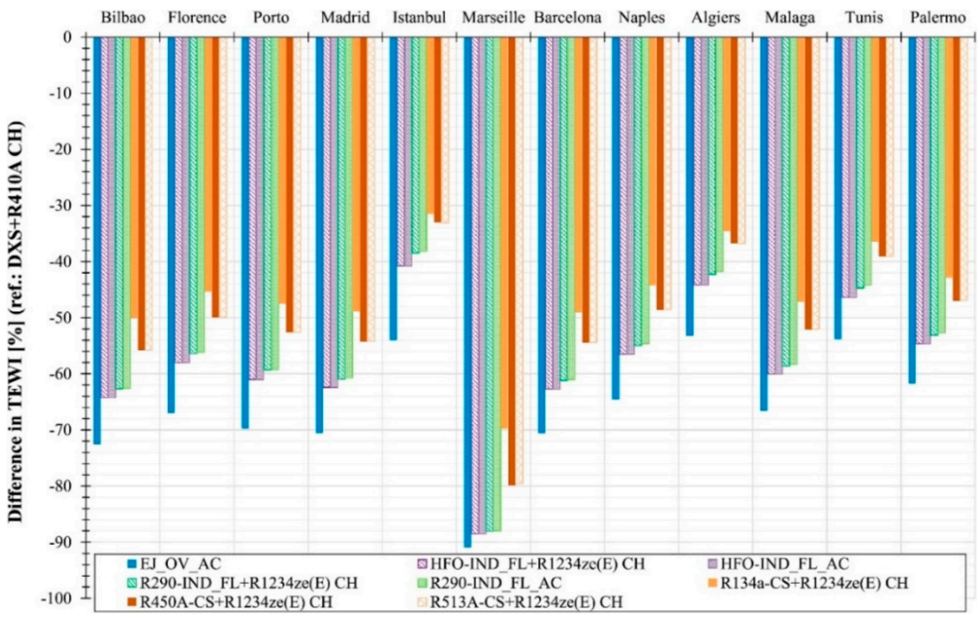


**Figure 25.** Difference in TEWI among various supermarket refrigeration solutions (DXS+R410A CH: R404A unit+R410A chiller; EJ_OV_AC: multi-ejector based system; -IND+R1234ze(E) CH: indirect arrangements+R1234ze(E) chiller; -CS+R1234ze(E) CH: cascade arrangements+R1234ze(E) chiller) in several locations positioned below the $CO_2$ equator ($t_{MT}$ = −4/−10 °C, $t_{LT}$ = −27/−35 °C, $t_{AC}$ = +3/+5 °C, $\dot{Q}_{MT}$ = 120 kW, $\dot{Q}_{LT}$ = 25 kW, $\dot{Q}_{AC}$ = 120 kW) [52].

### 3.4.3. Field Experimental Assessments

The data from filed gathered by Fredslund et al. [55] in various locations showed that energy reductions from 10% to 15% at roughly 30 °C can be attained.

The field measurements collected by Hafner et al. [21] demonstrated that energy reductions between 15% and 30% over the unit relying on parallel compression can be obtained, depending on the AC load and outdoor temperature (Figure 26). Also, the researchers measured values of pressure lift from 5 bar to 10 bar. The data were gathered from a supermarket located in Spiazzo (North of Italy) between the 1st of May and the 30th of October 2015 at external temperatures ranging from 22 °C to 35 °C.

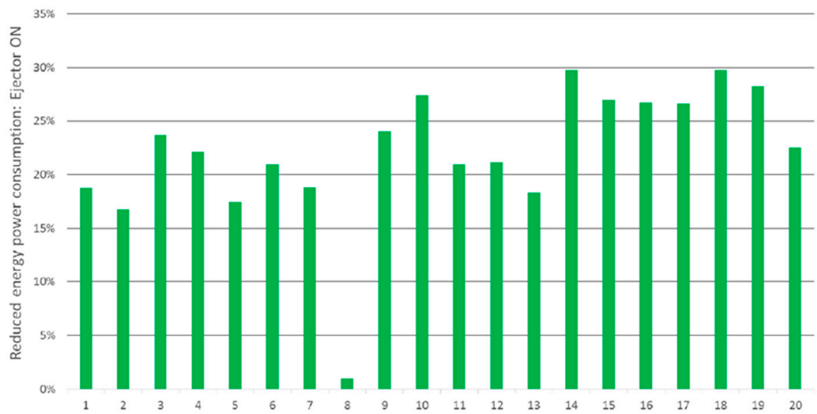


**Figure 26.** Reduction in energy power consumption [%] by recovering part of the available expansion work ($p_{MT}$ = 29 bar, $p_{LT}$ = 14 bar, $p_{lift,AC}$ = 5÷10 bar) [21].

### 3.5. High Ambient Temperature Countries

For climate reasons, the AC need as well as the refrigeration demand have a crucial relevance on economic, energy and environmental perspectives in high ambient temperature countries. The more the global warming effects become relevant, the more the cooling demand will increase, which will in turn accelerate climate change. According to [63], as a consequence of the enormous growth in cooling need related to emerging countries (typically hot areas), the energy reclaim for space cooling is expected to overtake space heating by 2060 and outstrip it by 60% at the end of the century. In addition, countries with emerging economies feature massive use of high-GWP refrigerants and have only recently begun the transition from hydrochlorofluorocarbons (HCFCs) to eco-friendlier working fluids, including R744.

To highlight the interest in multi-ejector based solutions in hot climates too, it is worth remarking that Middle East's first "$CO_2$ only" refrigeration plant was recently installed in a supermarket (2000 $m^2$, heat recapture implementation, $t_{MT}$ = −2 °C, $t_{LT}$ = −25 °C) in Al-Salam (Jordan). This plant was described as a test for commercial "$CO_2$ only" refrigerating units operating in high ambient temperature climate context [64].

The theoretical study by Kvalsvik et al. [65] showed that a transcritical $CO_2$ supermarket refrigeration unit presenting two multi-ejectors modules features 53% higher power input than separated R410A-based units at the design outdoor temperature of 45 °C. However, the energy benefits associated with the use of overfed evaporators were not assessed as well as the evaluation should have been performed on an annual basis.

Singh et al. [66,67] highlighted with the aid of experimental data that R744 ejector supported parallel vapor compression systems with and without integration with the AC equipment offer stable operations at high outdoor temperatures.

Blust et al. [68] experimentally showed that a multi-ejector unit is a feasible solution for the Indian climate context. The results obtained suggested that a maximum value of exergy efficiency of 0.387 can be achieved at an AC evaporator temperature of 12 °C, a MT evaporator temperature of −6 °C, a LT evaporator temperature equal to −29 °C, intermediate pressure of 52 bar and R744 gas cooler exit temperatures of 46 °C.

Singh et al. [69] implemented an experimental campaign based on an AC evaporator temperature between 7 °C and 11 °C, a MT evaporator temperature of −6 °C, a LT evaporator temperature equal to −29 °C, intermediate pressure of 44 bar and R744 gas cooler outlet temperatures between 36 °C and 46 °C. The results revealed that a maximum total *COP*, a maxim cooling *COP* and a maximum exergy efficiency equal to 4.2 (at 36 °C), 2 (at 36 °C) and 0.315 (at 46 °C) can be accomplished.

Singh et al. [67] experimentally showed that reductions in parallel compression consumption up to 10.7% can be achieved by ranging the intermediate pressure between 44 bar and 48 bar at R744 gas cooler exit temperatures between 36 °C and 46 °C. The assessment was carried out by considering an AC evaporator temperature between 7 °C and 11 °C, a MT evaporator temperature of −6 °C and a LT evaporator temperature equal to −29 °C.

The experimental assessment by Singh et al. [66] proved that the use of liquid ejectors leads to an increase in operating pressure of MT evaporators by 4.5% as well as a decrease in compressor power input by 5.5% at the R744 gas cooler exit temperature of 46 °C. The MT evaporators operated at −6 °C in dry-expansion running modes.

## 4. Other Applications

As mentioned above, $CO_2$ represents a promising working fluid for several applications. The peculiar properties of R744 make this refrigerant particularly suitable for water heating [70,71]. Cecchinato et al. [72] experimentally showed that an air-cooled $CO_2$ chiller for commercial refrigeration presents *COP* values between 3.1 and 2.0 at outdoor temperatures from 18 °C to 35 °C. However, reversible transcritical R744 heat pumping units are still limited to niche sectors in warm areas owing to the substantial energy efficiency penalizations taking place in AC mode [73]. The adoption of a two-phase ejector allows a R744 heat pump unit to attain the same seasonal efficiency as a R410A system in residential applications located in mild climates (i.e., north-east of Italy) [73]. Further energy advantages are supposed to be obtained with the aid of enhancement strategies similar to those implemented for supermarkets (i.e., multi-ejector concept adoption, direct heating and cooling) [10,73].

### *4.1. Theoretical Assessemnts*

Schoenenberger and Fraga [74] theoretically estimated that a multi-ejector based "$CO_2$ only" vapor-compression system has an average value of *COP* 3.6% lower than that of the reference R717/R744 cascade arrangement with secondary loop. The evaluation was based on industrial application and the climate context of Valencia (Spain). The selected baseline was the most preferred ultra low-GWP alternative to the currently employed units (i.e., R507A-based solutions) for the investigated application, i.e., fish processing plant. However, the authors highlighted that the higher energy costs associated with R744 as the only refrigerant can be compensated by the reduction in maintenance costs (between 15% and 20% lower) as well as in investment cost (15% lower at the present time and 22% as a cost forecast for 2020) compared to the R717-based cascade system. As a consequence, in August 2017 two racks based on the schematic represented in Figure 27 were installed to substitute a R507A-based unit in a fish processing plant close to Valencia (Spain).

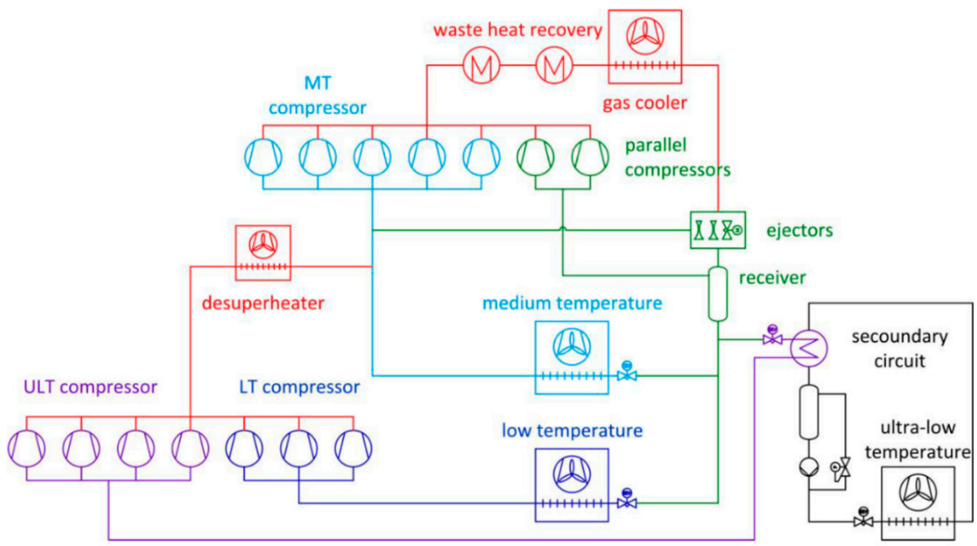


**Figure 27.** Schematic of the multi-ejector based "$CO_2$ only" vapor-compression systems installed in a fish processing plant in Valencia ($t_{MT}$ = +2 °C, $t_{LT}$ = −20 °C, $t_{ultra\ LT}$ = −40 °C, $\dot{Q}_{total}$ = 764 kW) [74].

The units featured evaporators being partially overfed at all the evaporating temperatures as well as heat recovery implementation devoted to produce hot water at +78 °C (heating capacity of 150 kW) for room cleaning, steam generation, etc. Another emerging application is currently related to reversible chillers for high energy-demanding buildings.

### *4.2. Laboratory Experimental Assessments*

The results obtained by Boccardi et al. [75] suggested that the throttling losses of a R744 air-to-water heat pump unit can be decreased by 46% by adopting the multi-ejector concept over the investigated running modes. However, the improvement in overall exergy efficiency was found to be, at best, equal to 9% in comparison with the basic solution.

Boccardi et al. [76] performed a sensitivity analysis on a multi-ejector $CO_2$ heat pump water heater (see Figure 28) considering the ejector area ratio, the compressor frequency and the outdoor temperature. The outcomes obtained showed the existence of an optimal multi-ejector configuration, as depicted in Figure 29a. In addition, the evaluation revealed that the optimum ejector performance does not coincide with the best performance in terms of *COP* and heating capacity (Figure 29b). This implies that the performance of the ejector can be enhanced by improving its design. Finally, it was found that it is needed to switch from an ejector configuration to another in order to maximize the performance with respect to the external temperature (Figure 29c).

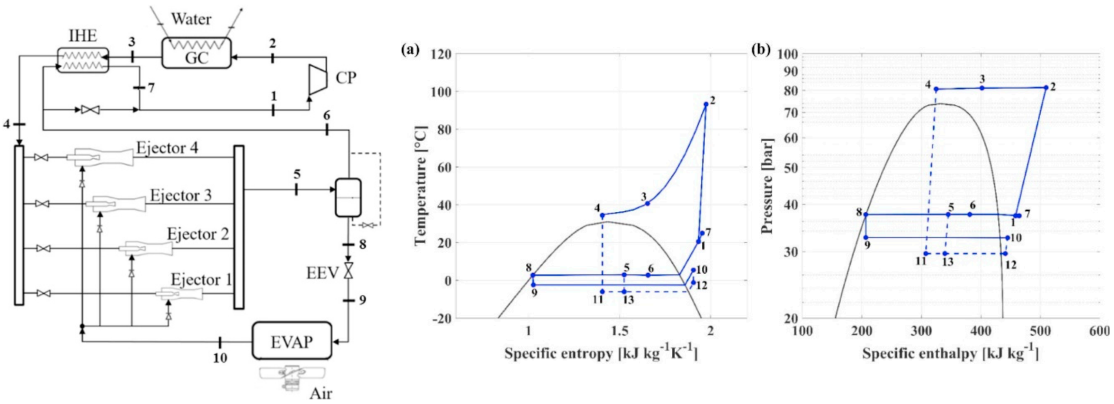


**Figure 28.** Schematic of the multi-ejector R744 air-to-water heat pump unit (left-hand side) and its T-s (**a**) and p-h (**b**) diagrams [76].

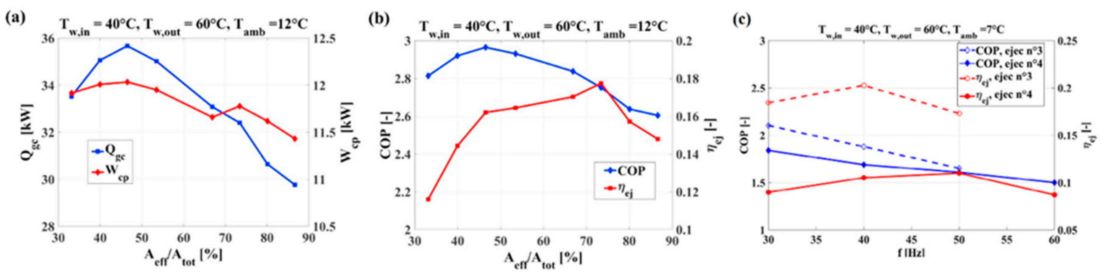


**Figure 29.** (**a**) Heating capacity (left) and compressor work (right) variations as a function of the overall ejector cross section; (**b**) *COP* (left) and ejector efficiency (right) variations as a function of the overall ejector cross section; (**c**) *COP* (left) and ejector efficiency (right) as a function of the compressor frequency [76].

Boccardi et al. [75,76] also evaluated ejector efficiencies below the ones available in the open literature. This was due to the fact that a multi-ejector module designed for refrigeration applications (i.e., high pressure lift and low mass entrainment ratio) was used.

Singh et al. [77] experimentally assessed the performance of a transcritical R744 heat pumping system equipped with multi-ejector block aimed at hot water production in the Indian climate context.

The results showed that total *COP*s between 7.2 and about 4 and *COP*s in cooling mode between 4 and about 2 can be achieved at R744 gas cooler outlet temperatures from 36 °C and 46 °C. The evaporating temperature was ranged between 7 °C and 9 °C during the experimental campaign.

## 5. Conclusions and Future Work

The development of the multi-ejector concept has helped to consolidate the position of commercial transcritical $CO_2$ refrigeration systems as market-ready alternatives to HFCs in any climate context. Also, their reliability and feasibility have been widely proved via a relevant number of installations and considerable energy savings have been estimated as well as actual energy consumptions have been monitored and reported in the literature. However, many retailers are still reluctant to consider R744 as the sole refrigerant for supermarkets located in warm climates due to:

(1) The persevering non-technological barriers, amongst which the lack of awareness of available technologies at decision making level and the lack of trained installers and service technicians [78];
(2) The limited amount of available field measurements and economic evaluations, especially with respect to the latest proposed solutions (i.e., Units relying on two multi-ejector blocks and/or implementing direct heating and cooling fan coils and air curtains). The availability of such information would help to build confidence in these solutions and thus lead to finally open the doors to their market penetration in warm climates as well.

Also, the multi-ejector concept is perceived to be the key to promote "$CO_2$ only" vapor-compression systems in other high energy-demanding buildings (e.g., hotels, spas, gyms) located in warm locations. However, the implementation of multiple ejectors operating in parallel is at an early development stage in this sector. The proliferation of these solutions will heavily depend on the energy advantageous attainable by simultaneously adopting a multi-ejector block and overcoming the secondary fluid penalization via direct heating and cooling technique, especially in warm areas.

The aforementioned knowledge gap will be bridged with the aid of MultiPACK (www.ntnu.edu/multipack).

Finally, it is worth remarking that the multi-ejector concept is still in its infancy in high ambient temperature countries (e.g., India) and extensive energy, environmental and economic assessments based on field measurements are necessary.

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## Nomenclature

Symbols, abbreviations and subscripts/superscripts

| | |
|---|---|
| AC | Air conditioning |
| *COP* | Coefficient of Performance (-) |
| DHW | Domestic hot water |
| GWP | Global Warming Potential ($kg_{CO_{2,equivalent}} \cdot kg^{-1}_{refrigerant}$) |
| *h* | Enthalpy per unit of mass ($kJ \cdot kg^{-1}$) |
| HCFC | Hydrochlorofluorocarbon |
| HFC | Hydrofluorocarbon |
| HP | High pressure (bar) |
| HVP | High pressure electronic expansion valve |

Symbols, abbreviations and subscripts/superscripts

| | |
|---|---|
| HX | Heat exchanger |
| IHX | Internal heat exchanger |
| IP | Intermediate pressure (bar) |
| LP | Low pressure (bar) |
| LT | Low temperature (°C) |
| $\dot{m}$ | Mass flow rate (kg·s$^{-1}$) |
| MP | Medium pressure (bar) |
| MT | Medium temperature (°C) |
| ODP | Ozone Depletion Potential |
| $p$ | Pressure (bar) |
| $\dot{Q}$ | Heat transfer rate (kW) |
| RC&H | Refrigeration, cooling & heating |
| $s$ | Entropy per unit of mass (kJ·kg$^{-1}$·K$^{-1}$) |
| $t$ | Temperature (°C) |
| TEWI | Total Equivalent Warming Impact (ton$_{CO2,equivalent}$) |
| $\dot{W}$ | Power (kW) |
| Greek symbols | |
| $\eta$ | Efficiency [-] |
| $\Pi$ | Suction pressure ratio [-] |
| $\omega$ | Mass entrainment ratio [-] |

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