DOI: 10.18462/iir.compr.2024.0696

SIMPLIFIED EJECTOR-SUPPORTED R744 BOOSTER SYSTEM

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ABSTRACT

Transcritical R744 booster systems are the preferred solution in commercial refrigeration. Technologies such as parallel compression and expansion work recovery are established to improve them. Previously, when installing energy efficient R744 refrigeration systems in warmer climate regions, it demanded a higher level of complexity and investment costs to further improve these units.

This work presents the first measured field data of the Simplified Ejector-Supported Booster (SEB) system, benchmarked against a parallel compression system. The field data are gathered from two food retail stores in Portugal over a seven-month period. The results demonstrate that the SEB configuration outperforms the parallel compression (PC) system in terms of specific energy consumption under all ambient conditions.

Keywords: Commercial Refrigeration, R744, Ejector, Parallel Compression, Energy Efficiency

1. INTRODUCTION

R744 has gained significant attention as a refrigerant for various applications due to its minimal environmental impact, avoiding stringent regulations imposed on other refrigerants. [(EU) 2024/573] [ECHA PFASs Restriction] The adoption of transcritical R744 refrigeration systems has seen a market increase over recent years, with more than 84,000 transcritical units globally by 2023. These systems are particularly dominant in colder regions. However, their implementation in regions with elevated temperatures is also rising, albeit with the challenge of maintaining energy efficiency. [ATMO Report] Elevated ambient temperatures necessitate higher CapEx due to the requirement for additional components to maintain system performance.

Recent improvements in R744 system layouts aim to address these challenges. [Pardinas et al.] has introduced a novel system layout that simplifies the overall structure, consequently reducing both CapEx and OpEx. The first laboratory test, which has been conducted at NTNU/SINTEF Varmeteknisk laboratoty has shown promising results.

In this article, measured operational data from the so called Simplified ejector-supported booster system are analyzed and benchmarked against a parallel compression system, located in the same region. This system was selected due to its proximity and a similar total cooling capacity of both units. The data was collected in two food retail stores, to provide a practical evaluation of the systems economic viability. The findings are expected to contribute to the ongoing discourse on sustainable refrigeration solutions, particularly in the context of reducing both environmental impact and costs.

2. SEB SYSTEM LAYOUT

The SEB is designed for the use in commercial refrigeration systems and is specially adapted for the application in the food retail sector. The aim of this concept is to achieve an efficient operation across a wide range of ambient conditions as well as a simplification of R744 ejector system layouts to reduce CapEx and OpEx. Fundamentally the configuration combines two common R744 cycle improvements, namely non-superheated MT evaporation with increased evaporation temperature, and an ejector with the innovative approach for a year-round use, avoiding complicated switching modes and components, to a special combination. Figure 1 shows a simplified P&ID to elucidate its main characteristics.

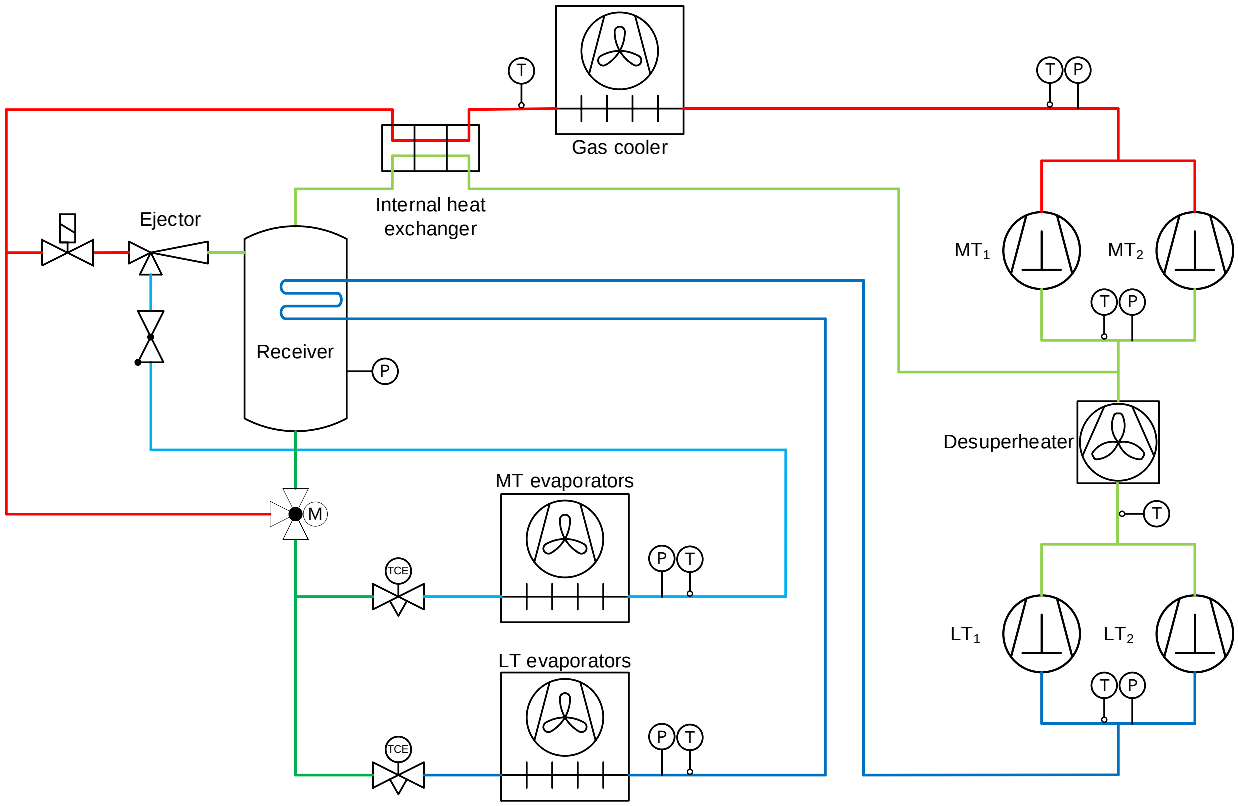

Figure 1: Simplified P&ID of the SEB system layout

In summary, the SEB system uses an ejector with only MT and LT compressor groups, unlike typical configurations with an intermediate receiver vessel. The LT compressors operate similarly to standard R744 booster systems, while the MT compressors handle both, the flow from the MT evaporators, via the low pressure receiver, and the discharge from the LT side. The ejector's role varies with the ambient temperature, operating actively in summer mode (SM) and passively in winter mode (WM). Furthermore, the strategic placement of the liquid receiver ensures the technology of non-superheated MT evaporation and elevated evaporation temperatures, i.e. MT suction pressures. A detailed elucidation and requirements for the components, especially for the ejector are given in [Pardinas et al.].

3. FIELD DATA

3.1. System setups

This work compares two food retail stores located in central Portugal. The first store utilizes the SEB configuration described in Chapter 2, henceforth referred to as SEB-Rack. The second store employs a parallel compression layout, supplemented by an additional flash gas valve to adjust the system at lower ambient temperatures and less flash gas content. In the following, this system is referred to as PC-Rack.

The SEB-Rack serves a public selling area of 1200 m², whereas the PC-Rack does only 600 m². Despite the difference in store size, the MT loads at design conditions are quite similar between the two systems as shown in

Table 1. However, there is a notable difference in the LT loads with the SEB-Rack handling 24.60 kW compared to 8.89 kW for the PC-Rack. Consequently, the MT/LT load ratio stands at 4.93 for the PC-Rack and 1.53 for the SEB-Rack.

Table 1: Characteristics of the consumers in the stores

	SEB-Rack		PC-Rack	
Consumer	Cooling capacity MT	Cooling capacity LT	Cooling capacity MT	Cooling capacity LT
cabinets	13.0 kW	19.2 kW	15.3 kW	1.0 kW
cold-storage-rooms	24.5 kW	5.4 kW	29.1 kW	8.0 kW
Total	**37.5 kW**	**24.6 kW**	**44.4 kW**	**9.0 kW**

To meet the respective cooling demands, the compressor configurations for both systems are shown in Table 2. The SEB-Rack employs two MT-stage compressors (MT_1 and MT_2) and two LT-stage compressors (LT_1 and LT_2) of similar sizes. Notably, the first compressor in each stage is inverter-driven, operating within a range of 25 Hz to 70 Hz.

In contrast, the PC-Rack utilizes similar compressors for the LT-stage, with one compressor being inverter-driven. For the MT-stage, two different compressors are used. The MT_1-compressor is smaller and inverter-driven, while the MT_2-compressor is larger and without variable speed control. Additionally, the PC_1-compressor, which is also inverter-driven, provides flexibility to maintain the energy efficiency at elevated ambient temperatures.

Table 2: Characteristics of the utilized compressors

	SEB-Rack			PC-Rack		
	Bitzer model	Displacement at 1450 RPM 50 Hz	Capacity control	Bitzer model	Displacement at 1450 RPM 50 Hz	Capacity control
MT_1	4HTEU-20LK	12.4 m³/h	Inverter	4MTE-10K	6.5 m³/h	Inverter
MT_2	4HTEU-20LK	12.4 m³/h	No	4FTE-20K	17.5 m³/h	No
LT_1	2FME-4K	6.36 m³/h	Inverter	2JSL-2K	3.48 m³/h	Inverter
LT_2	2FME-4K	6.36 m³/h	No	2JSL-2K	3.48 m³/h	No
PC_1	–	–	–	4PTE-7K	4.3 m³/h	Inverter

3.2. Data acquisition

The data acquisition for both stores was conducted over the period from December 2023 to June 2024. For the SEB-Rack, data was logged every ten minutes, while for the PC-Rack, it was logged hourly. Only standard measurement equipment, such as temperature sensors, pressure transmitters, and an overall energy meter, were utilized to simplify the data collection process. The electric energy measurements encompass the entire systems, including the racks with both MT and LT compressors, as well as the gas cooler and desuperheater.

3.3. Data analysis

The data analysis is focused on two primary parameters, the ambient temperature, and the energy consumption. The average temperature and the total energy consumption were calculated daily during the time between 12:00 PM and 05:00 PM. This specific time frame was selected for two reasons:

Higher ambient temperature: Given that the investigated operation period was conducted primarily during the colder days of the year, analyzing data during midday to afternoon hours ensures higher average ambient temperatures. This approach aimed to capture a wider range of ambient conditions, avoiding the lower temperatures of night and morning hours.

Operational efficiency: During this time slot, the refrigeration systems operated at higher capacities and ambient temperatures, leading to more relevant gas cooler outlet conditions for the primary flow in the SEB-Rack. Additionally, the higher ambient temperature increases the flash gas content, enhancing the operation of the parallel compressor in the PC-Rack.

For the comparative analysis, the specific energy consumption (E_{spec}) was calculated for each period using Equation 1.

$$E_{\mathrm{spec}}=\frac{E}{\dot{Q}_{0\ \mathrm{Con}}} \qquad (1)$$

E represents the average energy consumption and $\dot{Q}_{0\ \mathrm{Con}}$ the total consumer cooling demand at design conditions, including both total MT and total LT as illustrated in Table 1.

3.4. Results

The results of the field data are illustrated in Figure 2 and Figure 3. Both present the specific energy consumption, calculated using Equation 1, as a function of the average ambient temperature during a measurement. The diameter of the data points indicates the number of measurements considered for each point, with the smallest diameter representing a single and the largest indicating more than 15 measurements. An evaluation of the gas cooler pressure in relation to the ambient temperature revealed that both systems begin to operate in the supercritical area at ambient temperatures between 24°C and 25°C. The transcritical operation mode is marked in Figure 3.

For the PC-Rack, the evaporation temperature is maintained at t_0 = -10.5°C across all ambient conditions. In contrast, the SEB-Rack operated with different evaporation temperatures depending on the season. In winter mode (WM) (Figure 2) the evaporation temperature is set to t_0 = -4°C. In summer mode (SM) (Figure 3), the evaporation temperature was adjusted to t_0 = -8°C to ensure sufficient primary flow for the demanded pressure lift and the entrainment of the ejector.

The specific energy consumption for the PC-Rack is not changing much at temperatures below 14°C followed by a moderate rise until 24°C. Beginning with 24°C a substantial increase is observed, coinciding with the start of transcritical operation and the rising impact of the parallel compressor.

In winter mode, the specific energy consumption of the SEB-Rack shows a linear increase from 5°C to 13°C ambient temperature before it remains at a constant level. There is a small outlier at 14°C where the specific energy consumption is slightly lower, though the reasons for this anomaly are unclear.

In summer mode, the SEB-Rack exhibits an increase in specific energy consumption up to 24°C, followed by a substantial rise beyond this temperature. The enhanced rise corresponds to the onset of transcritical operation. Notably, there is an exception at 25°C, where the specific energy consumption is relatively low, but this point represents only a single measurement.

Overall, both figures demonstrate that the SEB-Rack performs better at all conditions and operation modes in terms of specific energy consumption compared to the PC-Rack. In winter mode, the energy efficiency of the SEB-Rack is particularly evident at ambient temperatures between 15°C and 20°C. At 20°C the SEB-Racks advantage peaks with an improvement of 60%. In summer mode, while both systems experience an increase in specific energy consumption at about 24°C because of the beginning of the transcritical operation, the SEB-Rack also outperforms the PC-Rack. The improvement peaks at 28°C with the SEB-Rack being about 34% more efficient.

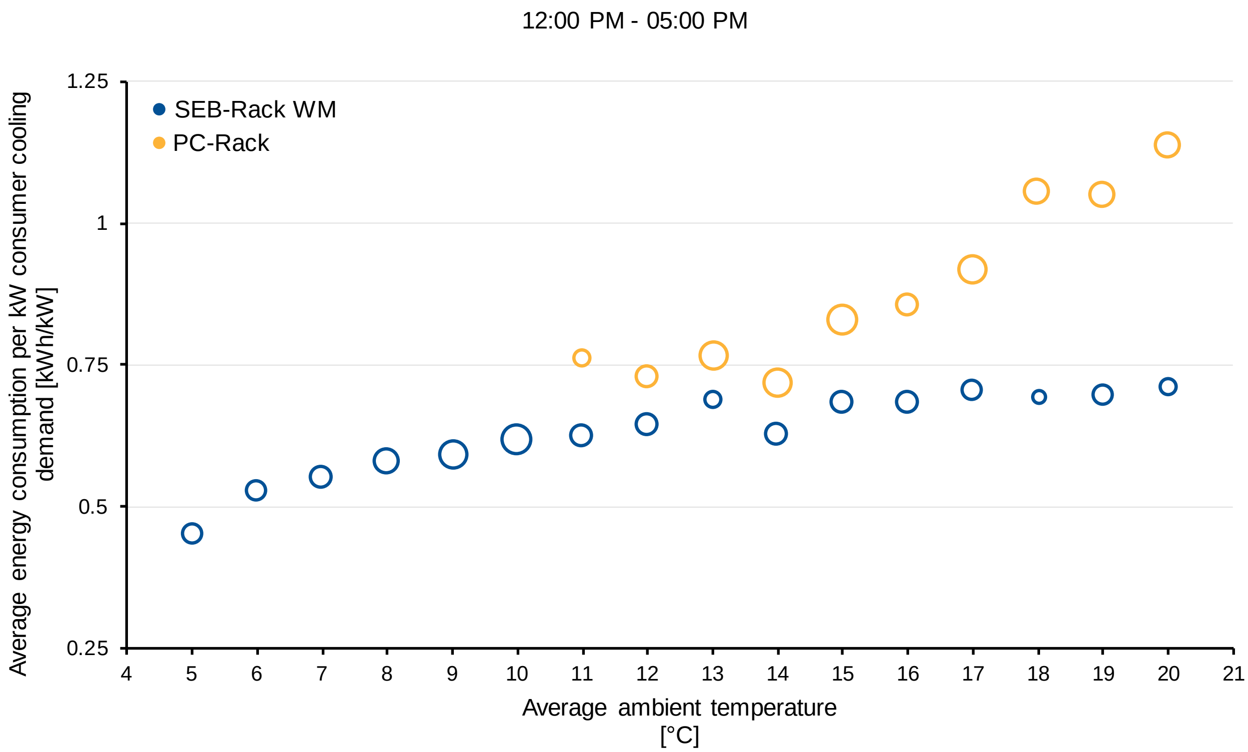

Figure 2: Comparison of the SEB-Rack working in winter mode and the PC-Rack

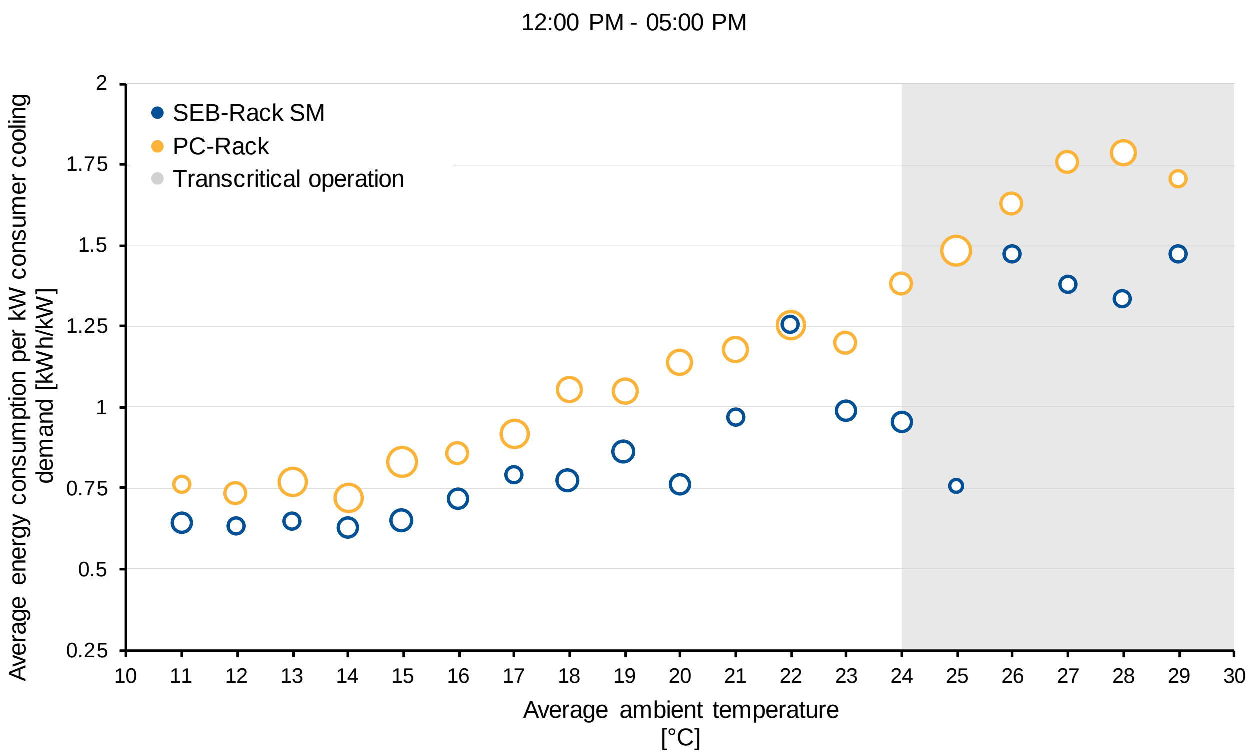

Figure 3: Comparison of the SEB-Rack working in summer mode and the PC-Rack

4. CONCLUSION

This work presents the first field data obtained by a Simplified Ejector-supported Booster system and the benchmark against a parallel compression system. The data were gathered in two food retail stores located in Portugal. The results highlight the potential of the SEB to perform efficiently under varying ambient conditions. Particularly in winter mode, the SEB maintained the specific energy consumption at a low level. Even in summer mode, despite a reduction in evaporation temperature, the SEB-Rack still outperformed the PC-Rack.

While the SEB system already shows a promising performance, there is room for improvement. Maintaining the high evaporation temperatures from winter mode throughout the summer will further enhance the energy efficiency. Additionally, a more detailed analysis of the parameters controlling the superheat of the evaporators is necessary to ensure that the system operates with overfed evaporation.

In the future, the SEB configuration will be compared with other transcritical booster systems to confirm the maximal efficiency improvements achieved here of 60% in winter mode and 34% in summer mode. This further work will focus on a similar MT to LT cooling load ratio to obtain more significant results.

NOMENCLATURE

CapEx	capital expenditures	E	average energy consumption (kWh)
LT	low temperature	E_{spec}	specific energy consumption (kWh/kW)
MT	medium temperature	$\dot{Q}_{0\ Con}$	total consumer capacity
OpEx	operating expenses	t_0	evaporation temperature
PC	parallel compression		
SEB	Simplified Ejector-supported Booster		
SM	summer mode		
WM	winter mode		

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