Modelling and development of high-pressure-lift ejector for low temperature evaporators in R744 refrigeration systems for supermarkets

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ABSTRACT

Decreasing the complexity of R744 commercial refrigeration systems for supermarkets could substantially reduce their cost, promoting worldwide spreading.

Typically, the share of the low-temperature (LT) load in the total load for supermarkets is low. Nevertheless, significant investments must be made to cover this demand, including dedicated compressors, inverter, desuperheater, oil management equipment, etc.

The objective of this paper is to describe and numerically validate a new concept based on high-pressure-lift ejector to support LT evaporators. This solution reduces the cost of the system by replacing the whole LT compressor section with a fixed geometry ejector. In addition, elimination of the compressor(s) allows overfeeding operation of LT evaporators.

The paper explores application range of this concept, using a 0-dimensional model of the refrigeration system.

Keywords: Commercial refrigeration, R744, Ejector, Parallel compression

1. INTRODUCTION

As broadly concluded (e.g., Gullo et al., 2018), efficient R744 refrigeration systems are currently able to outperform HFC-based units for supermarkets across Europe, thanks to the implementation of different technologies improving energy performance, such as overfed evaporators, vapour ejectors for unloading the medium-temperature (MT) compressors or AC production (Pardiñas et al., 2018), as well as mechanical subcooling (Karampour and Sawalha, 2018), among others. Still, that continuous adoption of more and more sophisticated technical solutions for boosting of energy performance made the system layouts and control strategies more complex, elevating the investment costs for 'all-in-one' R744 solutions above the level of typical HFC units (Gullo et al., 2018). Therefore, researchers and manufacturers need to find the compromise between the system efficiency, complexity, and capital costs in order to maintain the increase in number of installed transcritical CO_2 refrigeration units that has been occurring during the current decade.

While a lot of research attention was dedicated to the system optimization for the MT load, AC load or Heat Reclaim (HR) (Pardiñas et al., 2018, Gullo et al., 2018), relatively moderate efforts were put into the investigation of upgrading of the low-temperature (LT) section, where improvement might mean both lower energy consumption or/and lower investment costs. Some researchers (Gullo et al., 2017) concluded that by applying flooded LT evaporators with elevated evaporation temperature (supported by internal heat exchanger and suction accumulator in the LT suction line for compressor protection) one can decrease the annual energy consumption even by ca. 25%, for the refrigeration capacity ratio (called also load factor and defined as ratio of MT refrigeration load to LT refrigeration load) equal to 4.8. Another study (Karampour and Sawalha, 2018) claimed to

have effectively elevated the LT evaporation temperature from -32 °C to -29 °C by using flooded mode, which resulted in less frosting in addition to energy savings. However, apart from this relatively obvious trend to eliminate superheating also in the LT cabinets, no direct use of more advanced techniques, like for example vapour ejectors for refrigerant circulation in the LT cabinets, has been reported so far for supermarkets.

The concept of ejector-supported freezers has been previously widely studied for domestic refrigerators, specifically for isobutane (Liu et al., 2010, Wang et al., 2014). Various layouts for two-evaporation-level systems for household refrigerator-freezers were evaluated, finding the improvement in COP compared to a baseline cycle (without ejector) up 10% (Jeon et al., 2018). Moreover, a modified dual-temperature CO_2 transcritical refrigeration cycle, in which two cascade ejectors were applied to enhance the performance of a refrigerator-freezer, eliminating the LT compressor entirely, was proposed (Bai et al., 2017). Compared to a basic dual-evaporator cycle without ejectors, the authors claimed to have obtained up to 25% improvement in energy and exergy efficiency, for evaporation temperatures typical for the supermarket applications and load factor equal to 1.

The potential for ejector implementation to invoking circulation in the LT cabinets in a transcritical R744 system will be always determined by load factor (Bai et al., 2017). This is particularly true for booster configuration for supermarkets, where the pressure difference applied in individual expansion devices in cabinets is in practice fixed, independently of the ambient conditions, fixing thus pressure lift of the LT ejector. Typical load factors for supermarkets of different size around Europe range between 2 and 8 (Gullo et al., 2017), for evaporating temperatures ranging from -10 °C to -2 °C for the MT section and from -35 °C to -25 °C for the LT section (Gullo et al., 2018). An interesting feature of the LT cabinets is that, due to the relatively low product temperature, they are usually equipped with doors, which results in an almost constant load profile throughout the year and the day. This, along with the substantially fluctuating MT or AC loads, entails typically fluctuating load factor conditions, which imposes more demanding off-design operational regime for a potential LT ejector.

On the other hand, refrigerant circulation in the LT section supported purely by ejectors (no LT compressors) enables elevation of the evaporation temperature and running in flooded mode, which reduces pressure lift of the LT ejector.

State-of-the-art "all CO_2" refrigeration systems encompass a separate group of dedicated LT compressors, at least one of them usually equipped with a variable speed drive (VSD) for managing the potential changes in load, oil-feeding systems, safety systems, etc. Replacement of all those components with a single ejector (or battery of several ejectors in parallel) supporting the LT cabinets could reduce the investment costs. Therefore, the objective of this paper is to describe and numerically validate a new concept based on high-pressure-lift ejector to support LT evaporators and reduce the complexity and cost of transcritical CO_2 refrigeration systems.

The paper explores application range of this concept, using a 0-dimensional model of the refrigeration system.

2. CONCEPTS INVESTIGATED

Several ejector-supported LT section concepts have been evaluated numerically to compare the energy performance of the pack. This section describes (i) the state-of-the-art booster unit supported by parallel compression, treated as a reference layout (Fig. 1, left side), (ii) an upgrade that allows overfed MT evaporators (Fig. 1, right side), and two novel configurations with the (iii) upstream-gas cooler split and (iv) downstream-gas cooler split LT ejector replacing the dedicated LT compressors (Fig. 2, left and right side, correspondingly).

Fig. 1 left illustrates the state-of-the-art booster unit supported by parallel compression. Two groups of compressors, MT and LT compressors, are devoted to keeping the evaporation temperature at the cooling and freezing cabinets or rooms, respectively. Both groups of evaporators are supplied by liquid refrigerant from the bottom of the liquid receiver, and it is usual that each evaporator has an individual expansion device that adjusts the flow of refrigerant depending on the demand. State-of-the-art systems try to regulate the flow so that there is a certain degree of superheat at the outlet of the evaporators and to guarantee that only vapour (superheated) reaches the suction of the compressors.
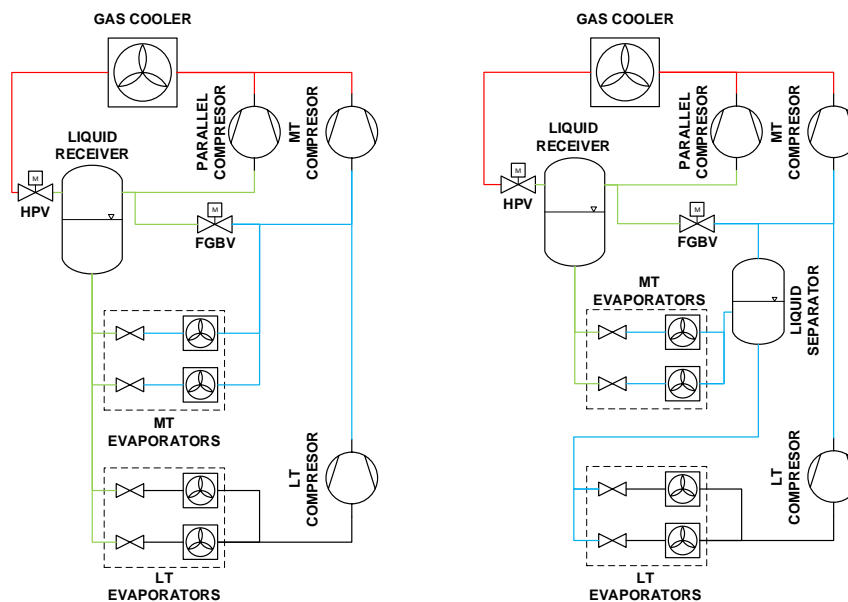
Figure 1: CO$_2$ refrigeration systems for commercial refrigeration with cooling (MT evaporators) and freezing (LT evaporators) cabinets. Left, traditional booster system supported by parallel compressors. Right, upgrade of the traditional booster system with overfed MT evaporators and active control of the liquid separator level

The third group of compressors, the so-called parallel compressors, regulate the intermediate pressure level at the liquid receiver by removing the flash gas. In case the amount of flash gas is low, which usually happens when heat is rejected at the gas coolers at low ambient temperature, it is the flash-gas bypass valve (FGBV in Fig. 1) that solely controls this pressure, by throttling vapour to the suction of the MT compressors. Heat is rejected to the ambient in the gas cooler, and the high pressure is regulated by means of the high pressure valve (HPV in Fig. 1).

The second configuration represented in Fig. 1 right is based on the previous layout with an auxiliary liquid separator downstream of the MT evaporators and two completely independent liquid lines added. This allows flooded operation of the MT evaporators, which reduces power consumption of the system, keeping the operational safety of the MT compressors uncompromised. The liquid level at the liquid separator is normally controlled by a pump or a liquid ejector, which returns liquid from the separator to the receiver. An alternative was proposed by EPTA (Mastrapasqua, 2017), which provides an additional liquid line from the separator to the LT evaporators. Thus, LT evaporators are fed from the separator if there is liquid in it, and from the receiver if the separator is empty.

The concept proposed in this study is a development of EPTA's solution, where the LT evaporators are always independently fed with liquid refrigerant from the liquid separator. This involves active control of the liquid level, by coordinated opening of the expansion valves at all the MT evaporators, which in addition leads to their flooded (and thus more efficient) operation.

Fig. 2 left shows the first ejector-supported LT section considered in this study. It is based on hot-gas-driven ejector(s) entraining the outlet stream leaving the LT evaporators, both vapour and small amounts of non-evaporated liquid. LT ejector discharges to the liquid separator, covering pressure lift in the range of 13 bar to 19 bar. The usual source of the driving stream would be the gas cooler outlet side, thus refrigerant at high pressure and relatively low temperature. However, first evaluation of this solution indicated that substantial amounts of liquid leaving the LT ejector and entering the MT accumulator would flood the liquid separator and in the end require a separate liquid return, e.g., dedicated liquid ejectors or pumps. Relatively high pressure lift that is requested entails very low entrainment ratio, i.e. relatively large motive mass flow rate is needed to entrain the vapour at low pressure. Consequently, motive flow from the discharge of MT and parallel compressors, upstream of the gas cooler (high pressure and high temperature and thus high expansion potential, reducing the requested motive nozzle mass flow rate), was considered as the suitable option for this LT ejector system.
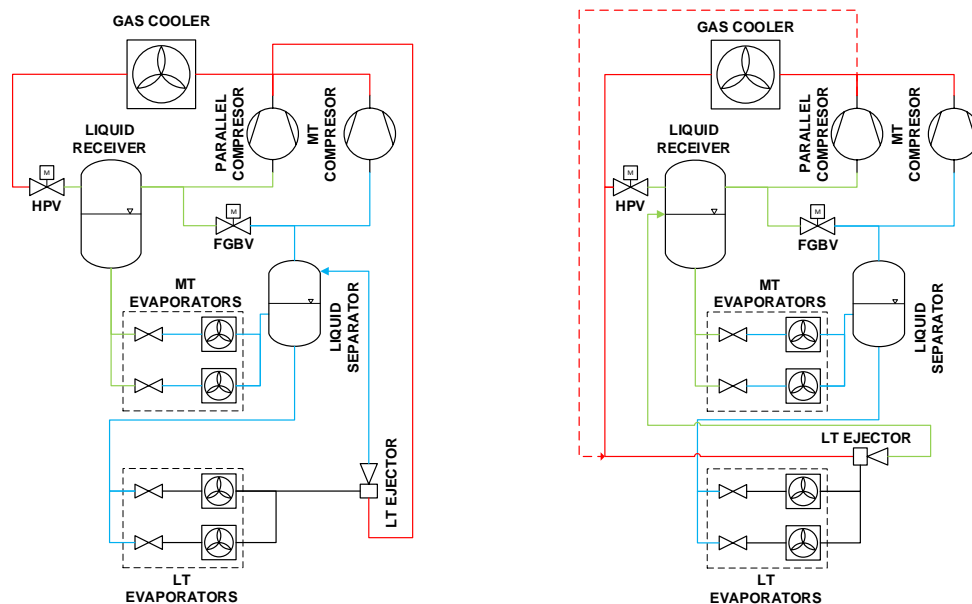
Figure 2: CO₂ booster system with LT ejector discharging to the liquid separator (left) or to the liquid receiver (right)

Another solution with LT ejector was proposed in this work, Fig. 2 right. The discharge port of the ejector is connected to the liquid receiver at intermediate pressure, involving even higher pressure lift (close to 25 bar). This discharge of the LT ejectors imposes no actual danger of flooding the liquid separator, so a standard source of driving stream could be used, i.e., gas cooler outlet. However, it was anticipated that this mass flow would be insufficient in practice, particularly as the gas cooler outlet temperature decreases and expansion work potential for the LT ejector motive nozzles diminishes. Consequently, an auxiliary line from the discharge of compressors (dashed in Fig. 2 right) should be implemented to support the motive flow if necessary, i.e., the overall mass flow rate flowing out of the gas cooler would not be enough to support the required LT capacity.

3. SIMULATION MODEL AND CONDITIONS

The four systems described in the previous section were modelled using Modelica object-oriented programming language in Dymola 2018 environment (Dassault Systems, Vélizy-Villacoublay, France). The models developed are based on TIL 3.5 library, and R744 properties are provided by the TILMedia 3.5 library, both from TLK-Thermo GmbH (Braunschweig, Germany). The effects of oil and of the oil management system were neglected.

Refrigeration capacities for cooling (MT evaporators) and freezing (LT evaporators) were selected in order to reflect typical size of a European supermarket (Gullo et al., 2017, Karampour and Sawalha, 2018). The design MT capacity was set at 100 kW (evaporation temperature -10 °C and superheating degree 8 K), while the LT capacity was assumed constant at 20 kW (evaporation temperature -32 °C and superheating degree 8 K). The design point at the outlet of the gas cooler was assumed at 40 °C, and the liquid receiver pressure at 40 bar (controlled by the parallel compressors). For these conditions, performance maps for real compressors by Bitzer were applied, as indicated in Table 1 (nominal frequency 50 Hz). The machines indicated in white cells were used as base design, the ones marked with grey background account for the extra capacity that was needed when the system used LT ejectors (and thus no LT compressors). Namely, a fifth MT compressor was needed for the system with LT ejector discharging to the liquid separator, meanwhile a third parallel compressor was added to cover the need for capacity with LT ejector discharging to the liquid receiver.

Table 1. Compressors selected for the model, and their displacements

MT Compressors	4MTC-10K (VSD)	4MTC-10K	4HTC-20K	4FTC-30K	4DTC-25K
Displacement [m^3/h]	6.5 (30 – 70 Hz)	6.5	12	17.8	21.2
PAR Compressors	4JTC-15K (VSD)	4JTC-15K	4FTC-30K		
Displacement [m^3/h]	9.2 (30 – 70 Hz)	9.2	17.8		
LT Compressors	2HME-4K (VSD)	2GME-4K			
Displacement [m^3/h]	4.34 (30 – 70 Hz)	5.05			

The compressor efficiencies were modelled with correlations dependent on the suction and discharge conditions, the rotational speed for VSD (variable speed drive) compressors. These correlations are based on published data from the manufacturer (Bitzer Software https://www.bitzer.de/websoftware/).

The gas cooler was modelled as a fin-and-tube heat exchanger, with a regulation of the volumetric flow of air so that the temperature at the outlet of the gas cooler ($T_{gc,out}$) could be adjusted for each simulation. High pressure was adjusted according to the optimum performance curve, i.e., setpoint was selected as a function of $T_{gc,out}$ and of the region of operation - subcritical, transcritical or transition. For subcritical operation ($T_{gc,out}$ equal to or below 25 °C), a subcooling degree equal to 3 K was set. Transcritical operation corresponded to $T_{gc,out}$ higher than or equal to 30 °C, where the pressure depended linearly on $T_{gc,out}$. The relation between both parameters is defined by the pair of points (30 °C,76.4 bar(a)) and (40 °C,102.4 bar(a)).

MT and LT evaporators were modelled also as fin-and-tube heat exchangers, where the volumetric flow of air was controlled to adjust the load for each simulation at each evaporator. For the state-of-the-art booster, with direct expansion (DX) evaporators both at the MT and LT, the aim for the regulation was achieving a superheating degree at the evaporators equal to 8 K. The booster system with overfed evaporators and liquid line from the liquid separators to the LT cabinets adjusted the opening of the MT evaporator expansion valve to keep the liquid separator level at half its capacity (LT evaporators running DX with setpoint for the superheat equal to 8 K). In both configuration with LT ejector, the control of MT evaporator expansion valve was as in the previous case (constant liquid level at separator). The LT evaporators ran overfed, which was modelled by adjusting the mass flow to attain quality at the outlet of the evaporator of 0.95.

Concerning the LT ejector model, for the sake of simplicity of the simulations, ability to continuous modulation of the opening degree (cross-section area of the flow-restricting channel, i.e., throat of the motive nozzle) was assumed for all the cases modelled. In practice a battery of several parallel ejector geometries could be used (stepwise control) or single geometry with modulated cross section area of the motive nozzle (continuous control with a regulating needle). Ejector of constant efficiency (defined as in Elbel and Hrnjak, 2008), equal to 25%, was assumed and applied in all the simulation cases.

Table 2 summarizes the main conditions and setpoints for the simulations for each of the four configurations presented. The MT evaporation temperature was considered 5 K higher for configurations with overfed evaporators than for those with DX evaporators. Similarly, the LT evaporation temperature was up to 7 K higher for the configurations with LT ejector (where overfed operation is possible) than for those with LT compressors. Simulations were performed with different load factors (defined in section one as the ratio of the MT refrigeration load to LT refrigeration load), kept always constant the LT load at 20 kW.

Table 2. Conditions and setpoints for the parametric study and for the different configurations tested: SAB (state-of-the-art booster), BOLS (booster with overfed MT evaporators due the liquid line at the liquid separator), LTEj_LS (LT ejector discharging to the liquid separator) and LTEj_LR (LT ejector discharging to the liquid receiver).

Configurations	SAB	BOLS	LTEj_LS	LTEj_LR
$T_{gc,out}$ [°C]	10 – 40 (5 °C intervals)			
$T_{evap,MT}$ [°C]	-10	-5		
$T_{evap,LT}$ [°C]	-32		-28 & -25	-25
MT Load [kW]	60, 80 & 100			
LT Load [kW]	20			
p_{LR} [bar(a)]	40			

4. RESULTS

Fig. 3 illustrates the main results of this study, which compare the different configurations proposed, grouped per load factor (5, 4 and 3 from top to bottom, respectively). The height of bars represents the ratio of the pack power consumption of a certain configuration to the pack power consumption of the reference configuration (state-of-the-art booster), at the same gas cooler outlet temperature.

It is clear in all cases that the pack power consumption decreases with the booster configuration with overfed MT evaporator and independent liquid line to the liquid separator (BOLS in Table 2) compared to the reference case, i.e. the ratio is always lower than 1 (in general between 15% and 5% lower). This effect was expected, as the evaporation temperature can be raised due to the enhanced operation of the evaporator.

Concerning the systems with LT ejector, in most cases the ratios were above the unity. Thus, the pack power consumption increases compared to the reference system when LT compressors are replaced by the LT ejector, even when LT ejector configurations account for the benefit of operating with flooded LT and MT evaporators. A separate analysis of the two configurations with LT ejector shows differences between them.

The first system with the LT ejector that uses hot gas as motive flow and discharging to the liquid separator (LTEj_LS in Table 2) always entails a significant increase of power consumption compared to the reference. The reason is the increased capacity at the MT compressors to supply the hot gas at the ejector, even if the entrainment ratio of the LT ejector with this hot gas is relatively high (from 0.17 to 0.53). The extra power consumption, in ratio, is higher if the load factor decreases.

The second option, with the motive of the LT ejector using as much flow from downstream of the gas cooler as possible and discharging to the liquid receiver (LTEj_LR in Table 2), shows different trends. With high gas cooler outlet temperature, and particularly with load factor equal to 5, the reference unit is outperformed by this solution of LT ejector. This good result is a combination of the increased evaporation temperatures and the reduced or inexistent utilization of hot gas to support the gas cooler pressure at the setpoint. However, and increased flow of hot gas from the compressors' discharge is requested as the gas cooler outlet temperature and load factor decrease, deteriorating the performance of the solution.
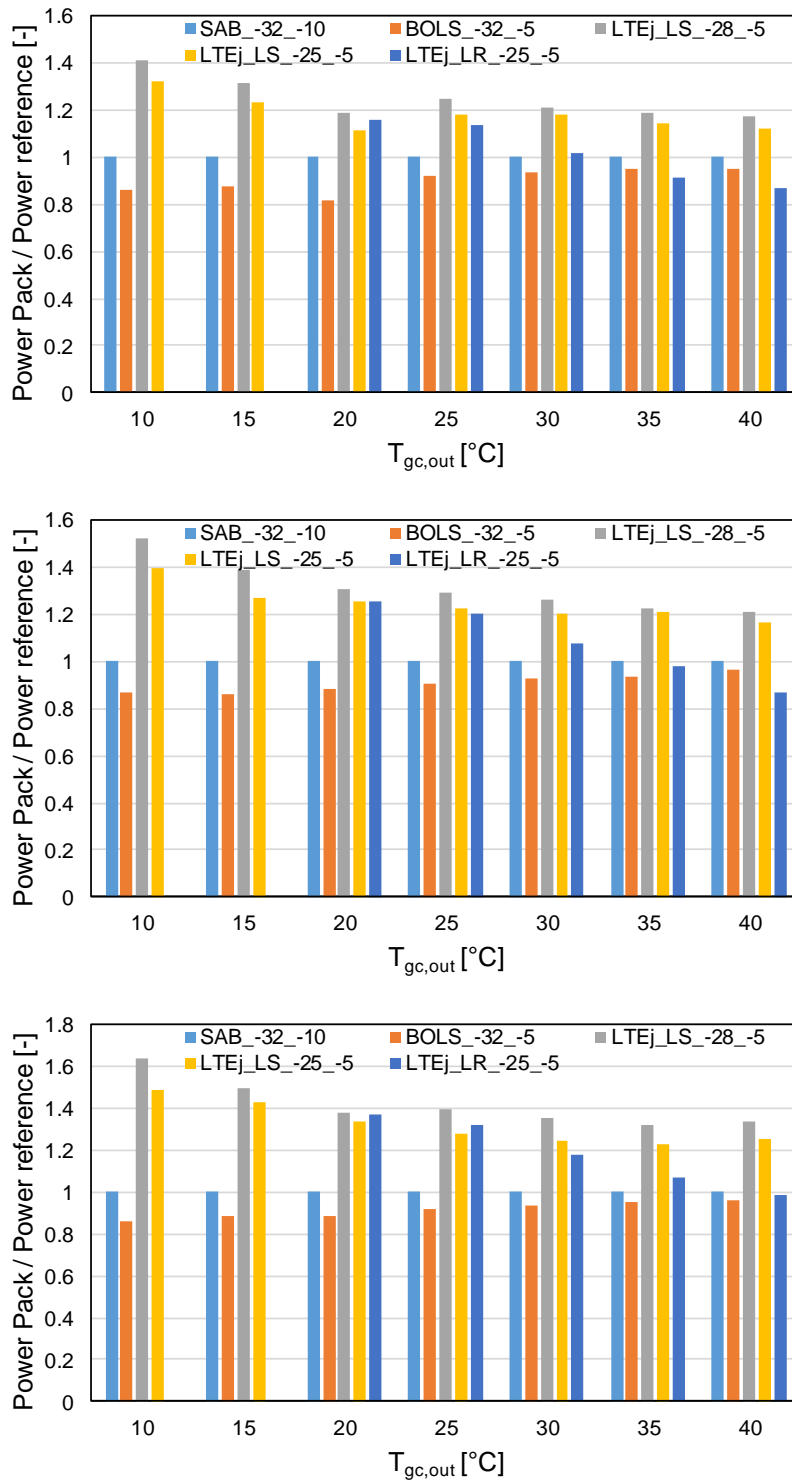
Figure 3: Ratio of the pack power consumption of a given configuration to the pack power consumption of the reference configuration (state-of-the-art booster) for the same gas cooler outlet temperature. The uppermost graph corresponds to load factor equal to 5, the middle graph to 4 and the bottom graph to 3. Abbreviation according to Table 2. The numbers indicated in the legend denote the LT and MT evaporation temperatures in degrees Celsius for each run of simulations

5. CONCLUSIONS

This study delved in different solutions to reduce the complexity of CO_2 booster systems for commercial refrigeration by replacing the LT compressors with auxiliary systems by dedicated high-pressure lift ejector(s). In general, such simplified layouts involve a deterioration of the system energy performance due to the pressure lift to be overcome and the use of hot gas as motive flow for the ejector. This deterioration is higher with low load fractions, i.e. with low ratio of MT refrigeration load to the LT refrigeration load.

A practical difficulty to be handled is proper design of a dedicated LT ejector geometry, enabling efficient energy performance (ejector efficiency not lower than 25%) at relatively high pressure lift, namely from 14 bar to 18 bar for the LTEj_LS configuration and 23-24 bar for the LTEj_LR configuration. Another challenge imposed on constant-geometry ejectors will be given by greatly changeable boundary conditions for the motive nozzle, from 50 bar/40 °C to 102 bar/115 °C, and from 60 bar/23 °C to 102 bar/45 °C for the LTEj_LS and LTEj_LR layouts, correspondingly.

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