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Experimental investigation of CO_2 systems for Indian supermarkets with parallel configuration of multiejectors (INDEE)

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ABSTRACT

Experimental investigation of transcritical R744 pack for Indian supermarkets was performed. Parallel combination of expansion work recovery multiejector blocks was applied for optimization of energy performance of the whole pack. The discharge pressure control proved to be fully functional with parallel multiejector operation providing system stability over a broad range of ambient conditions. Energy performance of the pack measured in Indian conditions was at the level recorded in the NTNU/SINTEF laboratory for a reference R744 pack. High ambient temperatures might result in operation on the verge of the operational envelope for compressor discharge temperature, especially for the MT machines.
Keywords: Supermarket, R744, Ejectors.

1. INTRODUCTION

Refrigeration systems for supermarkets solely based on carbon dioxide are currently able to outperform HFC-based units for 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. (2018a), as well as mechanical subcooling, Karampour and Salwaha (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). This effect, together with the lack of knowledge and experience with transcritical systems and their performance in tropical conditions results in the total absence of R744 in the Indian supermarkets, hotels and cold chain industry, for the sake of HCFCs and HFCs.
Initial studies show however that potential for application is great, even in the regions of India characterized by very hot climate. Namely, Purohit et al. (2018) found in their theoretical study that properly designed 'all-in-one' R744 systems (integrated all CO_2 booster with multiejectors and flooded evaporators) always outperform conventional HFC systems with direct expansion and superheated evaporators.
Typical design profile of refrigeration loads for supermarkets of different size around Europe is defined by the refrigeration capacity ratio (called also load factor and defined as ratio of MT refrigeration load to LT refrigeration load), typically 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, correspondingly, Gullo et al. (2018). Integration of AC is desired, however not always accepted by the shop owners. Integration of heating is in practice a standard design.
In Indian conditions load factor is somewhat lower (between 3 and 4) and the effect of AC cannot be neglected since AC constitutes ca. 50% of the overall load, Purohit et al. (2018). Also, in order to effectively compete with HFC systems, integration of the AC load in the 'all-in-one' R744 system is

a must. Integration of heating will naturally only further boost up the energy performance, due to very advantageous properties of CO_2 for heat reclaim. Therefore, appropriate design of the integrated compressor pack for Indian supermarkets becomes an issue of particular importance. The purpose of this paper is to present the first results registered at a demo transcritical R744 facility, emulating compressor pack for a small-size Indian supermarket. A specific feature of the rig elevating the energy performance, apart from complete integration (freezing + cooling + air conditioning + heating), is maintaining the discharge pressure solely with the use of multiejectors, i.e., total elimination of the high-pressure expansion valves.

2. SYSTEM DESCRIPTION

A demo R744 test facility for supermarket applications of 3 kW LT, 10 kW MT and 20 kW AC cooling capacity was developed in cooperation with ENEX, Danfoss, Dorin, LUVE and Klimal, and installed at IIT Madras, India (Figure 1), within the scope of project INDEE. The cooling system is designed to maintain three different levels of temperatures at the three shell-and-tube evaporators: freezing temperature (LT) at -29°C, refrigeration temperature (MT) at -6°C and air conditioning (AC) at 7-9°C. The test facility is also equipped with the glycol-based heat recovery system to maintain a constant heat load to the system (heat reclaimed in gas coolers is effectively used to supply evaporators). The excess heat is rejected in an air-cooled fin-and-tube gas cooler. Outlet conditions of MT and LT evaporators are controlled by Electronic Expansion Devices (EEV). Propylene glycol and water solution is used as a heat transfer medium in the test facility. Two separate glycol loop circuits are arranged with different glycol concentrations; 42% for MT & AC load and 56% for LT load.

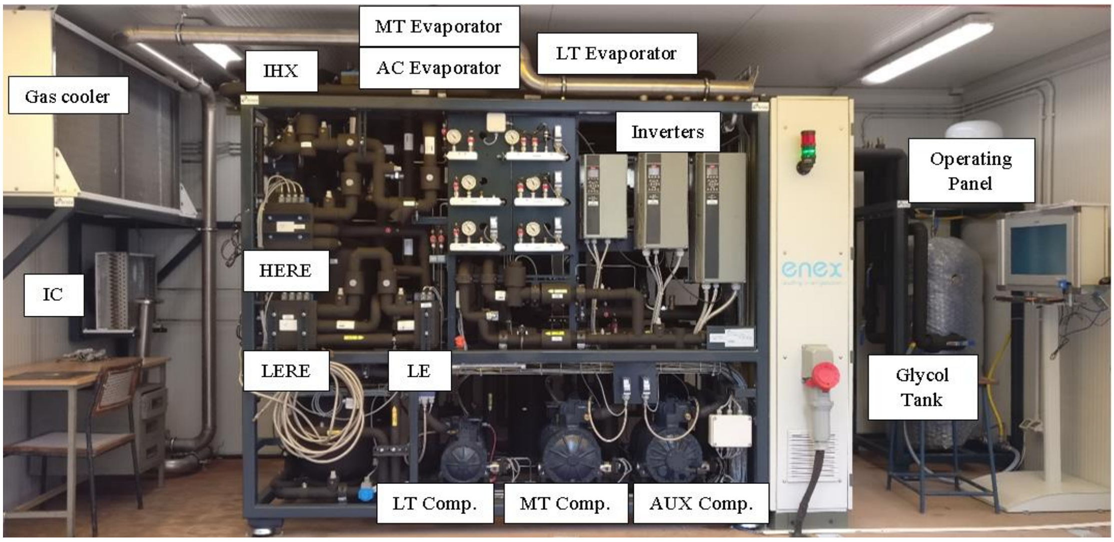

Figure 1: Layout of the transcritical R744 demo facility for Indian supermarkets at IIT Madras

Three piston compressors are arranged at various suction temperature levels (LT & MT and AUX compressors) to handle load as well as high amounts of flash gas. Two 4-cartridge vapour multiejector blocks by Danfoss (Multi Ejector Solution™) are installed in parallel, low entrainment ratio ejector (LERE) and high entrainment ratio ejector (HERE). One 2-cartridge liquid ejector block is also installed and connected to a suction accumulator to provide an excess feed to overflood the MT evaporators throughout the year (not indicated in Figure 2 for the sake of picture's clarity). Temperature sensors (PT1000), pressure sensors (piezoelectric cells), and flow meters (ultrasound flow meters for glycol circuits) are installed for system control and data acquisition.

The rig facilitates a few different operational modes to evaluate various possible configurations for supermarket application at high ambient temperature (up to 48 °C). Figure 2 shows the detailed schematic of the R744 test facility and various components installed in the system. The corresponding *p*-*h* plot for the present study is projected in Figure 3.

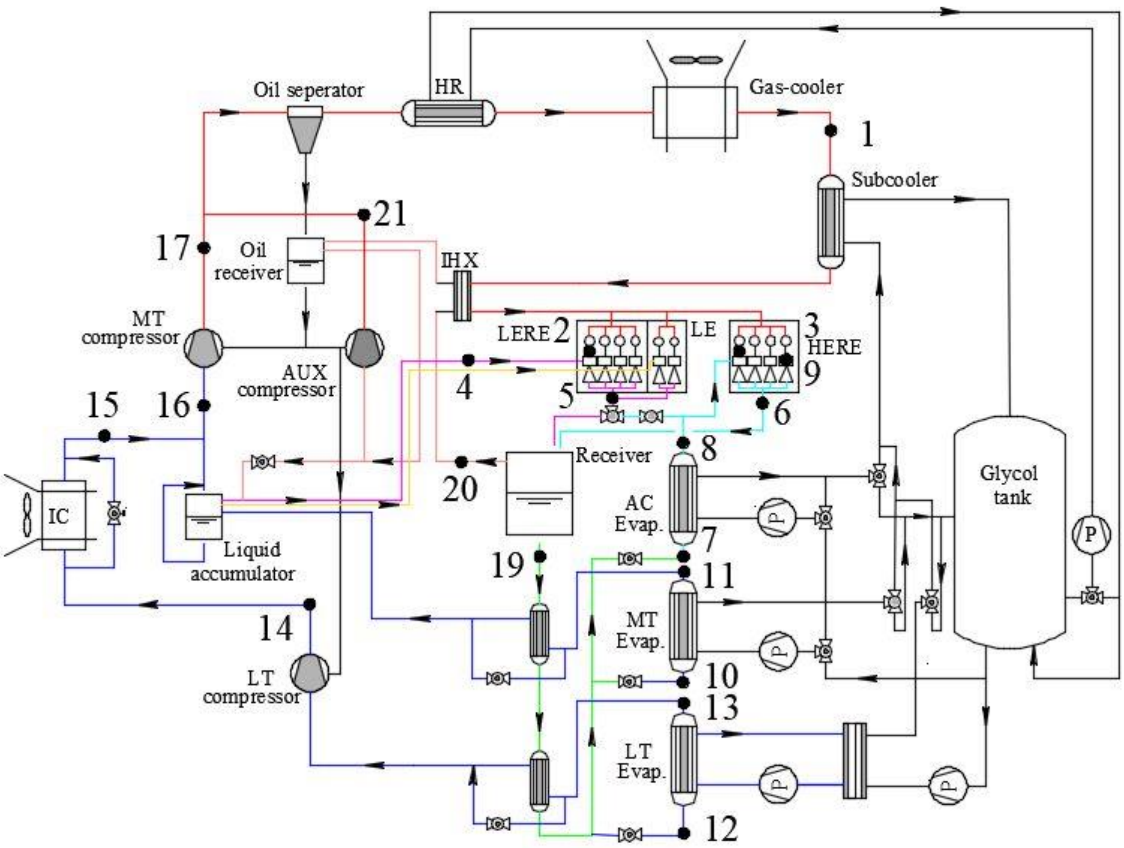

Figure 2: P&ID of the demo R744 system at IIT Madras. IC – intercooler (desuperheater), HR – heat reclaim, LERE – low-entrainment-ratio ejectors, HERE – high-entrainment-ratio ejectors, IHX – internal heat exchanger. For state points representation in *p-h* diagram see Figure 3

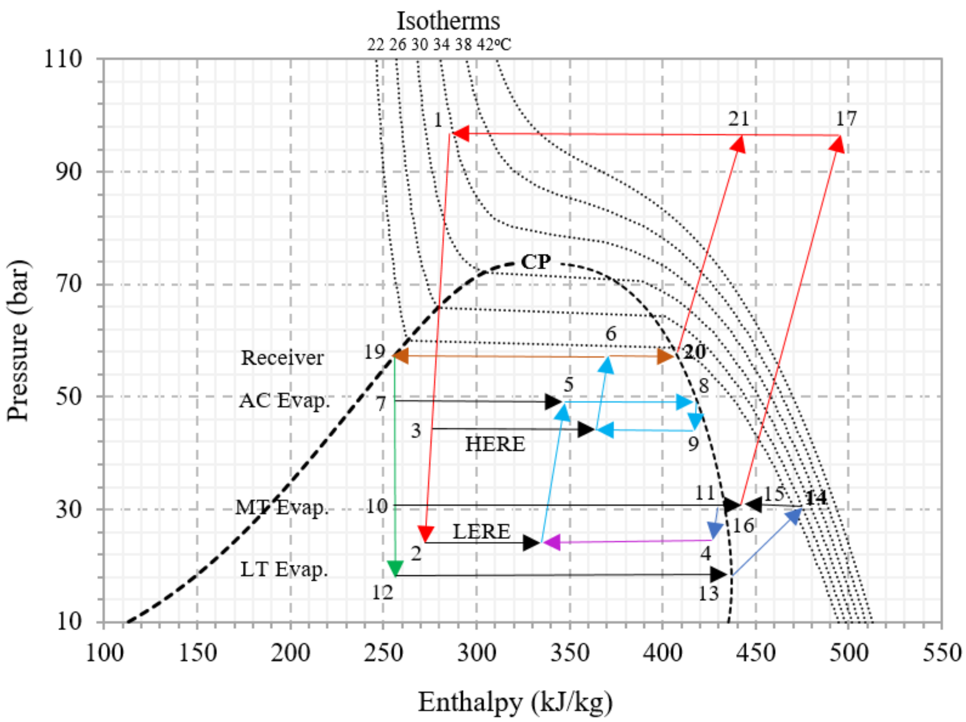

Figure 3. Cycle representation for the integrated LT, MT, and AC system for Indian supermarkets

3. TEST CONDITIONS

System layout investigated during the test campaign enabled maximum recovery of the expansion work potential available in the high-pressure gas cooler outlet stream, i.e., the potential available in the high-pressure stream leaving the gas cooler was effectively converted into suction effect in two independent multiejector blocks, HERE for AC production, and LERE for compressing part of the MT vapour to the receiver pressure.
The main device used to control discharge pressure were LERE ejectors (in auto mode) while HERE ejectors were switched on manually to invoke circulation in the AC evaporator. The range of operating conditions tested is given in
Table 1.

Table 1. Test conditions maintained during experimental campaign

Operating parameter	Units	Value/Range
Gascooler outlet temperature	°C	36 to 46
Gascooler outlet pressure	bar	86 to 108
AC evaporation temperature	°C	4 to 8
MT evaporation temperature	°C	-9 to -6
LT evaporator temperature	°C	-31 to -28
superheat	K	4 to 15
Receiver pressure	bar	43 to 46
IHX/heat reclaim	-	Bypassed/not included

4. ENERGY PERFORMANCE PARAMETER

The variety of technical solutions offered by manufacturers as an alternative to F-gases banned from 2020 (like R-404A) and the availability of very new integrated solutions for refrigeration and air conditioning based on CO_2 require a comparison of systems in terms of energy efficiency, rather than energy consumption. It claims for experimental methodologies, as consolidated and validated models for those systems are not yet available or affordable. Thus, a simplified approach based on measurement of power input and the comparison of the minimum ideal required power in the Carnot cycle is proposed. Namely, Power Input Ratio (PIR, see Figure 4) may be calculated for any ambient conditions and reference temperature levels of utilities (LT, MT, AC, heating, domestic hot water).

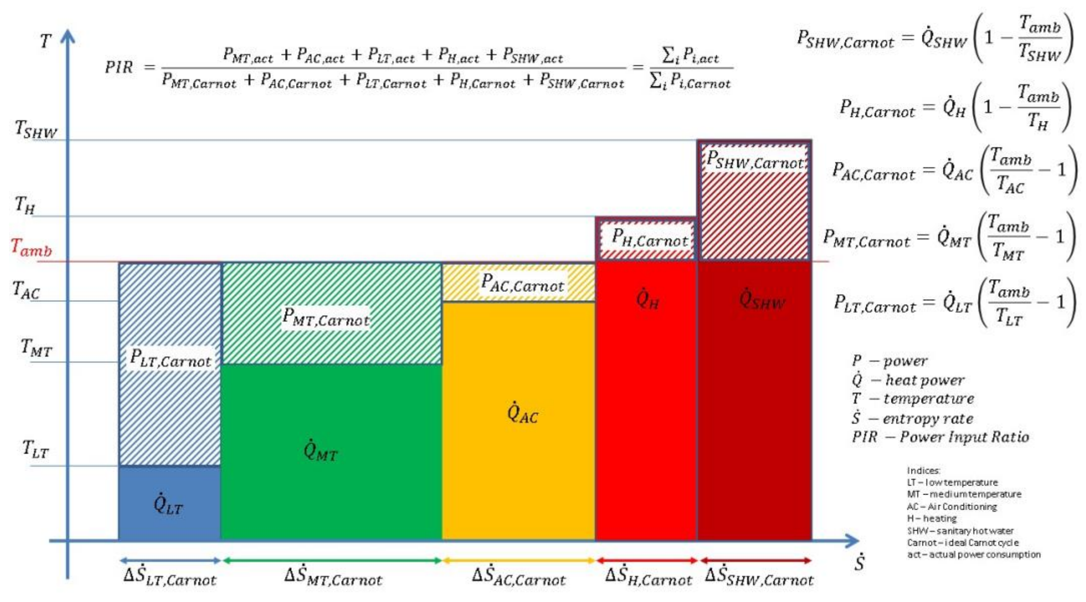

Figure 4. Definition of energy performance measure for integrated systems in supermarkets.

5. RESULTS

A dedicated test campaign was carried out for experimental investigation of (i) stability of discharge pressure control with two parallel multiejector blocks and (ii) energy performance of the system. 16 points were recorded, differentiated according to the emulated ambient conditions (it was assumed constant temperature approach in gas cooler equal to 3 K).

Table 2 presents an overview of the expansion duty distributed among various cartridges. It can be observed that fixing certain opening in the HERE block for AC generation does not reduce the ability of the LERE controller to maintain the requested discharge pressure, taken from the optimum energy performance curve. Average relative opening time less than 100% means that the ejector cartridge was actively adjusting the overall opening of the expansion nozzles in the block, being shut and open according to the steering signal sent by the discharge pressure controller. Thus, steady state test periods were in practice emulated with quasi-steady-state operation with discharge pressure fluctuating within certain narrow dead band (2 bar).

Table 3 shows basic parameters of the system in response to growing gas cooler outlet temperature. The most significant change one can observe is in the discharge temperature of the MT compressor, rising along with the ambient conditions, and reaching values close to not recommended by the compressor manufacturers due to the danger of thermal degradation of lubricant. At the same time, the energy performance, represented by PIR, reveals weak correlation to ambient conditions, showing even certain optimum around 37-39 °C.

Since the use of PIR has not been widespread so far, it is hard to find data for cross-checking whether the recorded values represent an up-to-date energy performance. Thus, own experimental data gathered in the course of the *Super-Smart Rack* project were utilized for comparison (Figure 5). For details on test rig and other experimental results on integrated R744 packs recorded during *Super-Smart Rack* see: Pardiñas et al. (2018b).

Table 2. Relative opening time of individual ejector cartridges for parallel operation of the HERE and LERE multiejector blocks

No.	Emulated ambient temp., °C	Gas cooler outlet temp., °C	Discharge pressure, bar	Average relative opening time (auto mode for LERE)				Average relative opening time (manual mode for HERE)			
				EJ1	EJ2	EJ3	EJ4	EJ1	EJ2	EJ3	EJ4
1	32.8	35.8	86.4	41%	12%	0%	0%	100%	0%	0%	100%
2	34.7	37.7	91.7	47%	44%	0%	0%	100%	100%	100%	0%
3	35.0	38.0	88.4	24%	25%	2%	0%	0%	100%	100%	0%
4	34.5	37.5	92.1	92%	6%	0%	0%	100%	0%	0%	100%
5	36.9	39.9	96.9	44%	56%	0%	0%	100%	100%	100%	0%
6	36.9	39.9	93.4	35%	17%	0%	0%	100%	100%	100%	0%
7	36.8	39.8	97.1	46%	54%	0%	0%	100%	0%	0%	100%
8	38.9	41.9	101.2	18%	82%	0%	0%	100%	0%	0%	100%
9	38.8	41.8	100.7	59%	0%	0%	0%	100%	0%	0%	100%
10	39.1	42.1	101.7	26%	74%	0%	0%	100%	0%	0%	100%
11	41.2	44.2	106.3	1%	99%	0%	0%	100%	0%	0%	100%
12	40.8	43.8	104.9	95%	1%	0%	0%	100%	0%	0%	100%
13	41.1	44.1	105.8	12%	88%	0%	0%	100%	0%	0%	100%
14	43.2	46.2	109.9	42%	58%	0%	0%	100%	0%	0%	100%
15	43.1	46.1	109.3	84%	1%	0%	0%	100%	0%	0%	100%
16	43.1	46.1	109.7	68%	32%	0%	0%	100%	0%	0%	100%

Table 3. Power Input Ratio of the system as a function of rising ambient conditions. Assumed utility temperatures: -18 °C for LT, +4 °C for MT, and +22 °C for AC

No.	Gas cooler outlet temp., °C	Receiver pressure, bar	MT discharge temp., °C	Evaporation temperature, °C			Load factor		PIR
				LT	MT	AC	$\frac{\dot{Q}_{MT}}{\dot{Q}_{LT}}$	$\frac{\dot{Q}_{AC}}{\dot{Q}_{MT}}$	
1	35.8	45.8	111.2	-29.9	-6.7	7.7	2.8	2.4	6.23
2	37.7	43.0	123.2	-29.8	-7.7	4.1	12.7	1.6	6.38
3	38.0	46.7	107.8	-28.4	-5.9	7.9	3.1	1.3	5.88
4	37.5	44.2	124.8	-29.2	-7.9	5.8	4.6	1.9	5.43
5	39.9	43.3	128.5	-29.4	-8.0	3.8	5.0	1.5	5.34
6	39.9	45.5	120.8	-29.3	-6.6	6.2	3.7	1.5	5.94
7	39.8	44.3	127.9	-26.8	-7.8	5.5	4.4	1.9	5.42
8	41.9	43.2	134.7	-29.3	-7.9	4.2	5.2	2.0	5.78
9	41.8	44.1	134.1	-29.0	-7.8	4.2	5.1	1.4	5.30
10	42.1	44.4	134.6	-29.1	-7.9	5.3	4.8	2.0	5.53
11	44.2	43.4	140.0	-29.2	-8.0	4.0	5.4	2.1	6.01
12	43.8	44.2	138.9	-29.3	-8.0	4.1	5.2	1.7	5.42
13	44.1	44.4	139.5	-30.8	-7.8	5.0	5.2	2.0	5.74
14	46.2	43.7	143.2	-28.2	-7.9	4.0	5.8	2.2	6.38
15	46.1	44.2	141.3	-29.2	-7.9	3.9	4.7	2.0	5.84
16	46.1	44.4	144.6	-27.7	-7.8	4.6	4.8	2.2	5.84

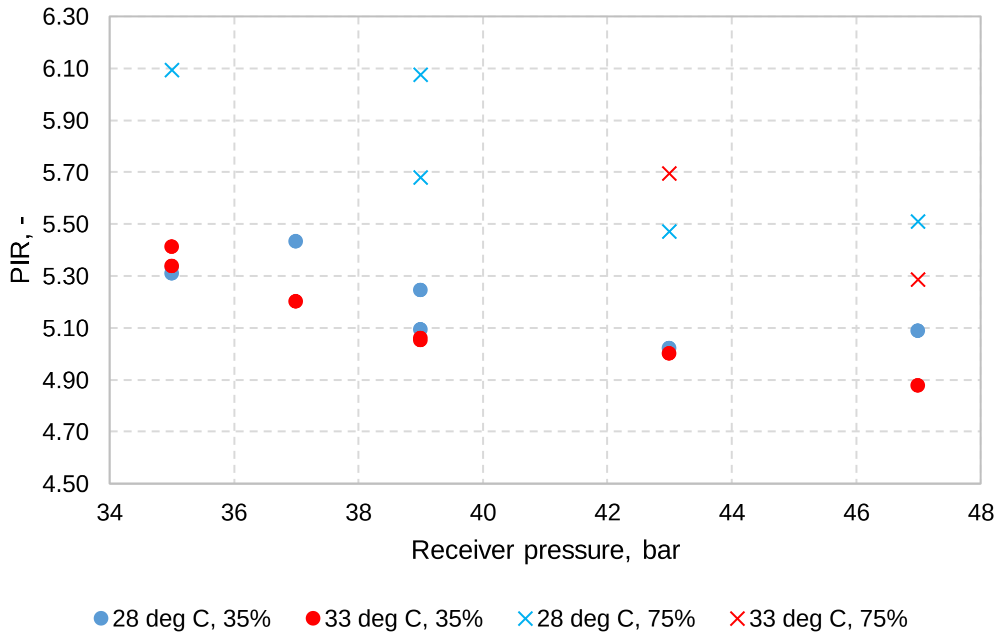

Figure 5. PIR for a reference transcritical R744 system investigated at SINTEF/NTNU laboratory during the KPN project *Super-Smart Rack*. Different colours denote gas cooler outlet conditions, while marker shape denotes load factor between AC and MT, according to the definition in Table 3. Load factor between MT and LT equal to 5; superheat conditions in all the evaporators

Points plotted in Figure 5 allow for comprehensive interpreting the results gathered in Table 3. Firstly, they confirm that the range of PIR values recorded during the INDEE-project test campaign does not differ significantly from what was recorded at a reference test facility. Secondly, it has been confirmed that PIR is practically not influenced by the ambient conditions. Finally, two important parameters that might have impact on PIR were revealed, namely (i) load factor between AC and MT, and (ii)

receiver pressure. Elevating the receiver pressure led to improvement in energy performance, at least in the investigated range, i.e., up to 47 bar. On the other hand, rising values of the AC/MT load factor deteriorate PIR. A possible explanation might be found in the fact that the AC load is burdened with greater specific entropy generation related to heat transfer between the evaporating refrigerant and the final utility. For example, the average temperature difference for data in Table 3 was equal to 11 K, 11.6 K, and 17 K for the LT, MT, and AC loads, correspondingly.
Nevertheless, an interesting point of the analysis could be making the integrated R744 cycle even more efficient, i.e., removing the main cycle inefficiencies. Apart from obvious features like using high-efficiency compressors or applying flooded evaporators (especially for ejector-supported AC evaporators where there is no danger of compressor flooding), an interesting aspect seems to be proper balancing of the receiver pressure. Firstly, due to the double-stage expansion layout, the intermediate pressure is one of the cycle degrees of freedom that should be optimized based on the overall energy performance, independently of the system complexity. Receiver pressure should be thus controlled according to the optimum-performance curve, like the discharge pressure. Secondly, the location of that optimum will be highly influenced not only by ambient conditions but also by actual performance of individual components like compressors and ejectors. For both compressors and ejectors the energy (and flow) performance is highly dependent mainly on requested pressure lift (or pressure ratio). For example, taking into consideration three quite similar test conditions according to the values of gas cooler outlet temperature, namely points, 2, 3, and 4, one can see that even small adjustments in the values of requested receiver pressure invoke non-negligible changes in PIR. The same observation applies to another pair, points 14 and 15.

Table 4. Compressor pressure ration for LT, MT and AUX machines together with pressure lift for HERE and LERE blocks

No.	Gas cooler outlet temperature, °C	Discharge pressure, bar	Receiver pressure, bar	Compressor pressure ratio			Pressure lift for HERE, bar	Pressure lift for LERE, bar	PIR
				LT	MT	AUX			
1	35.8	86.4	45.8	1.94	3.01	1.87	3.3	13.1	6.23
2	37.7	91.7	43.0	1.88	3.31	2.11	4.2	15.3	6.38
3	38.0	88.4	46.7	1.97	3.01	1.87	4.0	14.4	5.88
4	37.5	92.1	44.2	1.76	3.33	2.07	3.7	14.7	5.43
5	39.9	96.9	43.3	1.84	3.52	2.22	4.8	16.3	5.34
6	39.9	93.4	45.5	1.95	3.25	2.03	4.6	14.6	5.94
7	39.8	97.1	44.3	1.79	3.51	2.17	4.0	16.7	5.42
8	41.9	101.2	43.2	1.90	3.67	2.32	4.3	16.2	5.78
9	41.8	100.7	44.1	1.82	3.64	2.26	5.3	16.5	5.30
10	42.1	101.7	44.4	1.88	3.68	2.27	4.4	17.5	5.53
11	44.2	106.3	43.4	1.88	3.86	2.43	4.7	17.0	6.01
12	43.8	104.9	44.2	1.81	3.81	2.35	5.4	17.4	5.42
13	44.1	105.8	44.4	1.86	3.82	2.36	4.7	17.3	5.74
14	46.2	109.9	43.7	1.87	3.98	2.49	5.0	17.3	6.38
15	46.1	109.3	44.2	1.82	3.96	2.45	5.7	17.5	5.84
16	46.1	109.7	44.4	1.70	3.95	2.45	5.1	17.8	5.84

6. CONCLUSIONS

An initial test campaign of integrated transcritical CO_2 test facility designed to emulate typical working conditions in Indian supermarkets was carried out where parallel configuration of multiejector blocks was validated. The conducted experiments proved that parallel operation of HERE and LERE multiejectors is feasible and discharge pressure can be effectively maintained, regardless of ambient conditions. Very high ambient temperature (above 43 °C) may though impose hazardous working conditions for the MT compressor section, due to excessive discharge temperature (above 140 °C). Recorded energy performance, expressed with the use of newly introduced parameter PIR, proved to be within range typical for integrated R744 packs for supermarkets tested in European conditions. Still, substantial energy performance improvements can be harvested thanks to certain simple measures like controlling the intermediate pressure according to the optimum performance curve or flooded evaporators.

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