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A novel technology to adapt transcritical R744 supermarket refrigeration systems to rising temperatures

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ABSTRACT

In this work a novel technology to adapt transcritical R744 supermarket refrigeration systems to warm and hot climates as well as to rising temperatures was proposed and exhaustively investigated. The novel solution consisted of a booster device (increasing the transcritical fluid R744 pressure) followed by an air-cooled gas cooler and located between the conventional air-cooled condenser/gas cooler and high-pressure expansion valve. The results obtained revealed energy savings by from 2.31 % to 2.91 % in Seville (Spain) and from 4.64 % to 5.73 % in New Delhi (India). To further increase the energy benefits from the proposed technology, the use of an expander replacing the high-pressure expansion valve was also considered. As a consequence, energy savings by 7.80 % in Seville and 14.44 % in New Delhi with an additional investment recovery time of about 3 years in both of the selected locations were assessed.

Keywords: Carbon Dioxide, Clean Cooling, COP Improvement, Expander, Warm and Hot Climates

1 INTRODUCTION

The temperature of Europe is increasing faster than the global average, which can potentially lead to a dramatic impact on people's health, ecosystems and crucial services of modern society, such as supermarkets. As temperatures rise, in fact, supermarket refrigeration systems need to work harder to keep proper temperatures for food and beverages. Warmer outdoor air results in possibly compromised food safety and freshness as well as in higher electricity to run the refrigeration systems, thus in more greenhouse gas (GHG) emissions. Therefore, it is crucial to deploy supermarket refrigeration systems simultaneously featuring the use of refrigerants with negligible direct contribution to global warming and great energy efficiency at high outdoor temperatures.

Carbon dioxide is a non-toxic and non-flammable refrigerant (R744) offering low-to-zero global warming potential (GWP) and zero ozone depletion potential (ODP). Currently R744 is one of the most preferred working fluids for supermarket refrigeration systems (Gullo et al., 2018). However, the energy efficiency of R744 supermarket refrigeration systems is dramatically threatened by the occurrence of transcritical operating conditions happening at high outdoor temperatures (Sawalha et al., 2017). These energy performance penalizations are bound to occur more and more due to the aforementioned temperature rises. In order to overcome these energy performance penalizations, several technologies, such as parallel compression, overfed evaporators, ejector and various subcooling techniques, have been developed (Gullo et al., 2018). As examples, Javerschek et al. (2015) theoretically evaluated increases in coefficient of performance (COP) thanks to parallel compression by from 8.4 % to 13.6 % at outdoor temperatures between 25.0 °C and 42.5 °C. However, parallel compression is generally expensive, as it involves the use of one (or more) compressor(s). Therefore, the benefits from using the vapour injection technology were recently estimated by Jiang et al. (2025). Although the authors evaluated COP increases respectively by up to 32.14 % compared to a basic booster system and by up to 20.07 % compared to the solution with parallel compression, the vapour injection compressor is limited in capacity. As for overfed evaporators, Minetto et al. (2014a) experimentally measured energy savings by about 13 % compared to a traditional solution at the outdoor temperature of around 16 °C and the air temperature of nearly 0 °C by using liquid ejectors. Hafner et al. (2014) proposed the use of the multi-ejector concept, which was found to increase the COP by between 10 % and 20 % at outdoor temperatures from 15 °C to 45 °C in comparison with the basic solution. Nevertheless, ejectors feature a complicated and expensive control system. An alternative to the previously mentioned technologies is to cool down the R744 leaving the condenser/gas cooler by using the evaporator of either a vapour-compression chiller (Dai et al., 2021) or a heat-driven cycle (Guruchethan et al., 2023; Sengupta et al., 2024). However, the first technology is interesting only for small-sized applications, whereas the second one is still in its early stages. Paez et al. (2024) experimentally assessed COP enhancements by from 6.7 % (without decreased superheating degree) to 10.2 % (with decreased superheating degree) by using a subcooling system in transcritical regime compared to the basic arrangement. Gullo (2019) proposed the adoption of direct space heating and cooling to promote the adoption of transcritical supermarket refrigeration systems in warm and hot climates, whereas Suamir et al. (2012) suggested the integration of a cogeneration module fuelling an absorption cooling unit in cascade with a subcritical R744 supermarket refrigeration system.

The literature review above highlights the need for new simpler and more affordable technologies to enhance the performance of transcritical R744 refrigeration systems to further open the doors to supermarket applications in warm and hot climates as well as to deal with the temperature rise. Therefore, the target of this manuscript is to fill this knowledge gap by proposing a new technology aiming at enhancing the COPs of transcritical R744 supermarket refrigeration systems at high outdoor temperatures. Firstly, the operations of the R744 system with the novel solution were investigated and optimized to maximize the COP. At a later stage, the energy and economic performance of the R744 system with the new technology was compared to that of the conventional R744 system in two different locations, i.e. Seville (Spain) and New Delhi (India).

2 MATERIALS AND METHODS

2.1 Description of the novel technology

The conventional transcritical R744 supermarket refrigeration system, used as a baseline in this investigation, is schematized in Figure 1a, while its thermodynamic cycle is represented (in purple) in Figure 2.

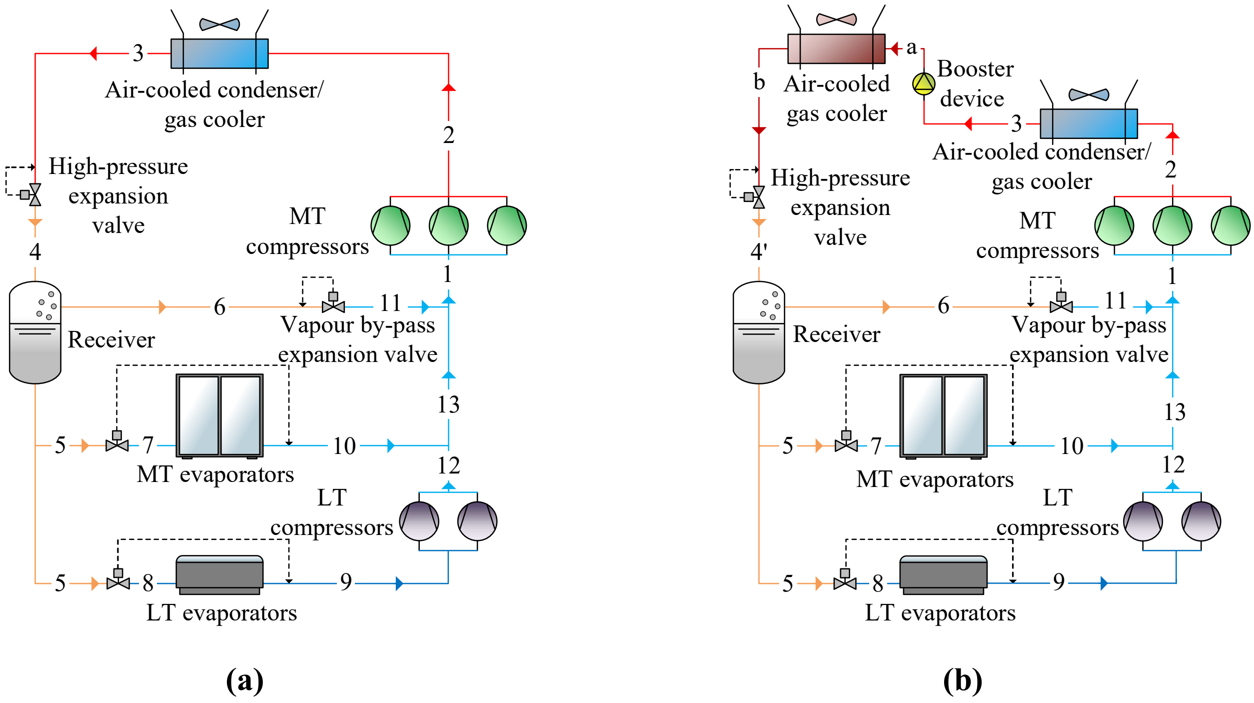

Figure 1: Schematic of (a) the conventional transcritical R744 supermarket refrigeration system (baseline) and (b) the transcritical R744 supermarket refrigeration system with the new proposed technology (i.e., with the booster device)

In the conventional system the medium temperature (MT) compressors draw the R744 as a superheated vapour (indicated as process 1 to 2), increasing their pressure from the MT pressure level to the high one. The R744 then enters the air-cooled condenser/gas cooler (process 2 to 3) where it rejects the heat into the outdoor air and it either condensates (in subcritical regime) or is cooled down (in transcritical regime). After the condenser/gas cooler the refrigerant is isenthalpically expanded (process 3 to 4) within the high-pressure expansion valve and then goes into the receiver where the R744 is split into its liquid part and its vapour one. Therefore, part of the saturated liquid leaving the receiver is isenthalpically expanded in the MT expansion valve (process 5 to 7) and vaporized in the MT evaporators (process 7 to 10), whereas the other one is isenthalpically expanded in the low temperature (LT) expansion valve (process 5 to 8) and vaporized in the LT evaporators (process 8 to 9). The vapour by-pass expansion valve makes the saturated vapour from the receiver expand isenthalpically (process 6 to 11). The superheat vapour leaving the LT compressors is then compressed to the MT pressure level (process 9 to 12), mixed with the refrigerant exiting the MT evaporators first (state 13) and then with the one leaving the vapour by-pass expansion valve, before being drawn by the MT compressors (state 1).

As showed in Figure 1b, the novel technology involves a booster device (process 3 to *a*) and an air-cooled gas cooler (process *a* to *b*) between the conventional high-pressure expansion valve (process *b* to 4’) and air-cooled condenser/gas cooler. The booster device is employed for slightly increasing the refrigerant pressure (i.e., requiring much less electricity to be run than compressors), while the air-cooled gas cooler is used for cooling down the refrigerant to the same temperature as at the outlet of the condenser/gas cooler (process 2 to 3). Figure 2 highlights that the R744 cooling after the air-cooled gas cooler (process *a* to *b*) allows the refrigerant to reduce its quality at the inlet of the receiver compared to the conventional system, translating into the less refrigerant mass flow rate being compressed by the compressors. Unlike the other subcooling techniques, the proposed technology requires relatively few added components with off the shelf standard components, as it only requires a gas cooler and a booster device, being similar to a pump/compressor and thus cheap.

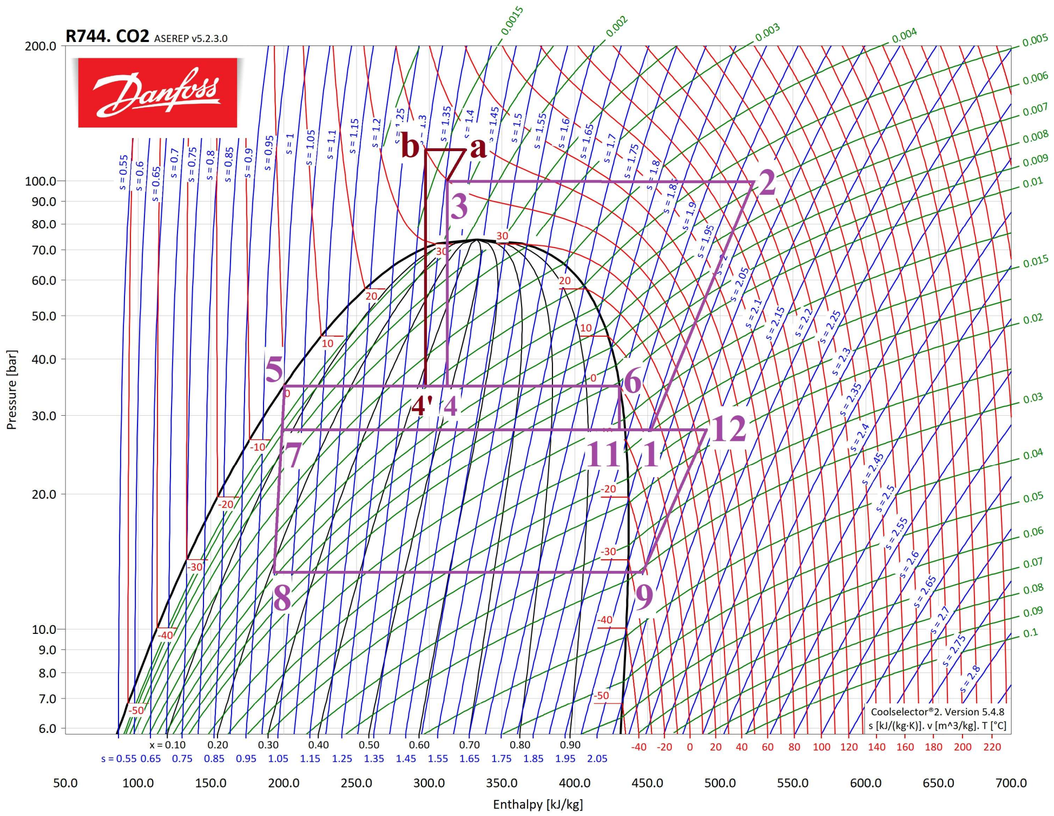

Figure 2: P-h diagram of the conventional supermarket refrigeration system and that of the supermarket refrigeration system with the new proposed technology (i.e., with the booster device)

2.2 Simulation models

The simulation models developed in this work were based on input parameters obtained from the field measurements of an actual Swedish supermarket (Karampour and Sawalha, 2018) and listed in Table 1.

Table 1. Input parameters (Karampour and Sawalha, 2018)

Parameter	Value
MT refrigeration load ($\dot{Q}_{MT}$)	if $t_{outdoor} \leq 10$ °C, then $\dot{Q}_{MT}$ = 100 kW else $\dot{Q}_{MT} = 4 \cdot t_{outdoor} + 60$ [kW]
LT refrigeration load ($\dot{Q}_{LT}$)	35 kW
MT compressor rack efficiency	$\eta_{MT\ compr} = -0.0144 \cdot \beta_{MT\ compr}^2 + 0.0719 \cdot \beta_{MT\ compr} + 0.5826$
LT compressor rack efficiency	$\eta_{LT\ compr} = -0.007 \cdot \beta_{LT\ compr}^2 \cdot 0.0153 \cdot \beta_{LT\ compr} + 0.6273$
MT evaporator temperature (t_{MT})	$t_{MT} = -8$°C
MT useful superheating	10 K
MT suction line superheating	10 K
LT evaporator temperature	$t_{LT} = -32$°C
LT useful superheating	10 K
LT suction line superheating	10 K
Receiver pressure	36.25 bar
Fan gas cooler power input ($\dot{W}_{gc}$)	$\dot{W}_{gc} = 0.03 \cdot \dot{Q}_{gc}$

Furthermore, the following additional assumptions were made:

- all the components were assumed to operate in steady-state conditions;
- all the assessments were carried out by using the mass rate and energy rate balances applied to each component of the investigated systems;
- all the expansion valves were assumed to operate isenthalpically;
- the variation of kinetic and potential energy in each component was considered negligible;
- the approach temperature of both the condenser/gas cooler and the gas cooler, i.e., temperature difference between the outcoming R744 and the incoming outdoor air, was taken as 2 K;
- minimum condensing temperature was assumed to be 9 °C;
- the condenser/gas cooler pressure was calculated using the approach suggested by Prins (2020);
- no pressure drops in the pipes and heat exchangers were considered;
- all the components were considered well-insulated;
- two values of the isentropic efficiency of the booster device were considered, i.e., 0.50 and 0.65, as they are unknown since this device is not on the market yet. However, it is expected that the booster device will have similar isentropic efficiencies of current transcritical R744 compressors.

Also, all the technological constraints of the components were respected. All the simulation models were implemented in MATLAB 2021b (MathWorks, 2021), while all the thermo-physical properties were evaluated by using CoolProp (Bell et al., 2014).

2.3 Implemented assessments

The performance of the solution showed in Figure 1b was firstly maximized in terms of COP and then compared to that of the baseline. At a later stage, an energy and economic assessment was also conducted considering two different locations, i.e., Seville and New Delhi.

Firstly, the annual energy consumption was calculated by using Eq. (1):

$$AEC = \sum_i \dot{W}_i \cdot f_i \qquad \text{Eq. (1)}$$

in which $\dot{W}_i$ is the total power (in kW) required to run the investigated systems at the *i*-th outdoor temperature, while f_i is the frequency of the occurrence (in hours) of the *i*-th temperature in a given year. The outdoor temperature bins (f_i) for the selected locations are presented in Figure 3.

Therefore, the annual energy savings (AES in %) offered by the proposed technology with respect to the baseline was computed using Eq. (2):

$$AES = \left(\frac{AEC_{new\ technology} - AEC_{baseline}}{AEC_{baseline}}\right) \cdot 100 \qquad \text{Eq. (2)}$$

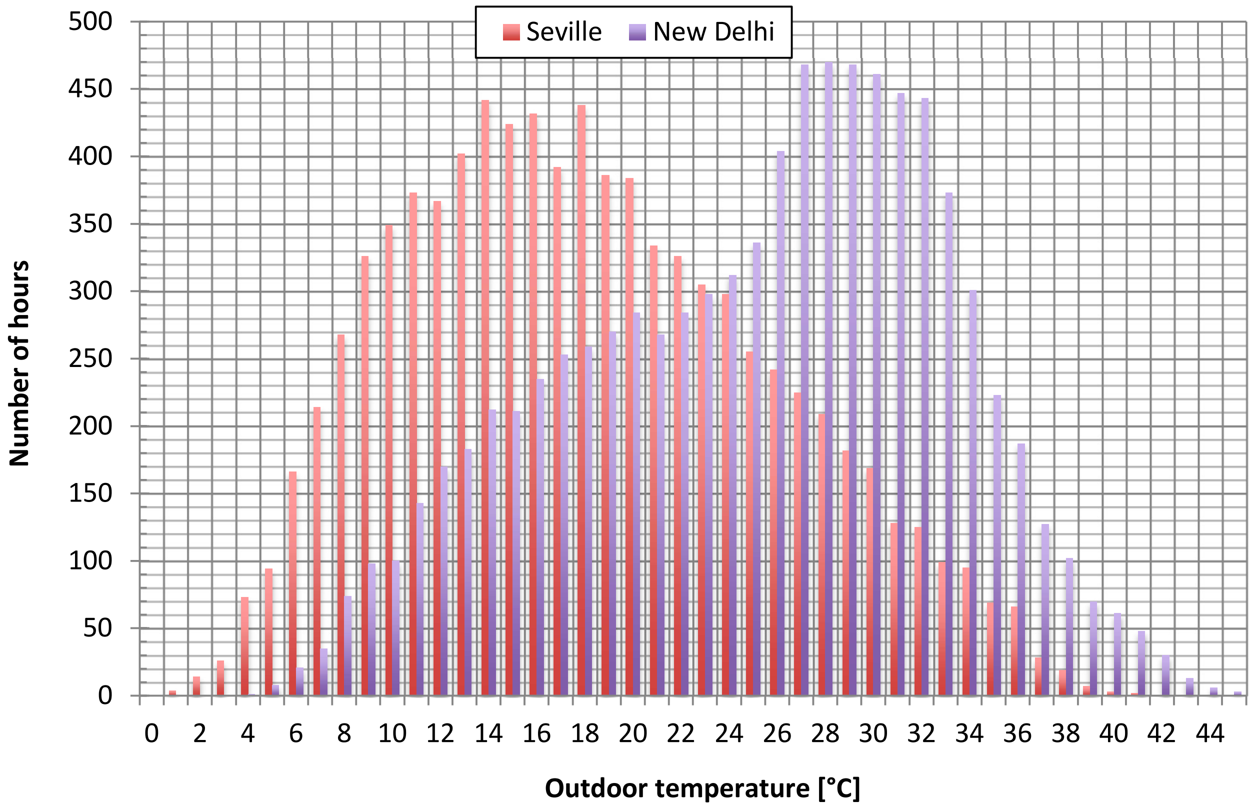

Figure 3: Bin hour outdoor temperature distribution in Seville (Spain) and New Delhi (India) (MeteoNorm, 2014)

The economic assessment was based on the calculation of the additional investment recovery time (AIRT) via Eq. (3):

$$AIRT = \frac{\Delta CC}{ES \cdot c_{electricity}} \qquad \text{Eq. (3)}$$

in which ΔCC is the increase in the capital cost (in €), ES is the energy saving (in kWh·year^{-1}) and $c_{electricity}$ is the average electricity cost (in €/kWh). In this study $c_{electricity}$ was taken as 0.222 €·kWh^{-1} in Seville (Spain) and 0.074 €·kWh^{-1} in New Delhi (India), respectively (GlobalPetrolPrices, 2024).

3 RESULTS AND DISCUSSION

3.1 Energy performance optimization and COP assessment

The first step of this work was to investigate on the needed operating pressure for the air-cooled gas cooler. The results involving isentropic efficiency of 50 %, outdoor temperature of 40 °C and different pressure ratio values for the booster device are presented in Table 2. The outcome obtained clearly revealed the existence of an optimal high pressure for the air-cooled gas cooler maximizing the COP. This conclusion can be justified by considering that the higher the pressure ratio was, the lower the R744 quality at receiver inlet was, resulting in a higher reduction of the R744 total mass flow rate and thus influencing the COP positively. However, the power input of the booster device also increased with the pressure ratio, affecting negatively the COP.

Table 2. Effect of the pressure ratio of the booster device on the performance of the transcritical R744 supermarket refrigeration system at $t_{outdoor}$ = 40 °C ($\eta_{booster\ device}$ = 0.50)

Pressure ratio [-]	1.10	1.20	1.30	1.37
Air-cooled gas cooler pressure [bar]	112.80	123.00	130.00	140.00
COP [-]	1.17	1.19	1.20	1.19
R744 quality at receiver inlet [-]	0.46	0.43	0.41	0.40
Booster device power input [kW]	6.39	11.90	16.91	20.26
Total compressor power input [kW]	192.99	183.63	177.82	174.80
Total R744 mass flow rate [$kg \cdot s^{-1}$]	1.90	1.80	1.73	1.70

At $t_{outdoor}$ = 40 °C the conventional system featured a COP value of 1.10, R744 quality at receiver inlet of 0.52 and R744 total mass flow rate of 2.11 $kg \cdot s^{-1}$. Thus, it can be concluded that the proposed novel technology could increase the COP by 9.1 % compared to the conventional R744 system at the optimal pressure of the air-cooled gas cooler of 130 bar. Similar conclusions could be drawn at $t_{outdoor}$ below 40 °C too. The main results at the optimal air-cooled gas cooler pressure for different $t_{outdoor}$ are summarized in Table 3. Increases in COP by from 0.9 % ($t_{outdoor}$ = 24 °C) to 9.1 % ($t_{outdoor}$ = 40 °C) were assessed, whereas no COP improvements were assessed at $t_{outdoor}$ below 24 °C.

Table 3. Optimal air-cooled gas cooler pressure for the supermarket refrigeration system with the new proposed technology (i.e., with the booster device) at different $t_{outdoor}$ ($\eta_{booster\ device}$ = 0.50)

$t_{outdoor}$ [°C]	24.00	25.00	30.00	35.00	40.00
Optimal air-cooled gas cooler pressure [bar]	73.82	82.30	94.00	112.80	130.00
COP [-]	2.18	2.09	1.73	1.43	1.20

The scenario involving an isentropic efficiency of the booster device of 0.65, whose main results are summarized in Table 4, was also investigated, revealing increments in COP by from 0.9 % ($t_{outdoor}$ = 23 °C) to 10.9 % ($t_{outdoor}$ = 40 °C). The outcomes at $t_{outdoor}$ below 23 °C are not reported in Table 5, as no COP improvements were evaluated.

Table 4. Optimal air-cooled gas cooler pressure for the supermarket refrigeration system with the new proposed technology (i.e., with the booster device) at different $t_{outdoor}$ ($\eta_{booster\ device}$ = 0.65)

$t_{outdoor}$ [°C]	23.00	25.00	30.00	35.00	40.00
Optimal air-cooled gas cooler pressure [bar]	72.30	82.30	94.00	112.80	130.00
COP [-]	2.27	2.12	1.75	1.45	1.22

3.2 Annual energy assessment

The annual energy consumption for the baseline was estimated to be equal to 596985.78 kWh/year in Seville and 915616.86 kWh/year in New Delhi, respectively. The energy savings offered by the new technology are presented in Figure 4. The results obtained highlights that the proposed technology offered limited energy saving in both of the selected locations, i.e., from 2.31 % to 2.91 % in Seville and from 4.64 % to 5.73 % in New Delhi, compared to the baseline. Therefore, it can be concluded that the new solution is not able to adapt transcritical R744 supermarket refrigeration systems equipped with the high-pressure expansion valve to rising temperatures as well as to warm and hot climates.

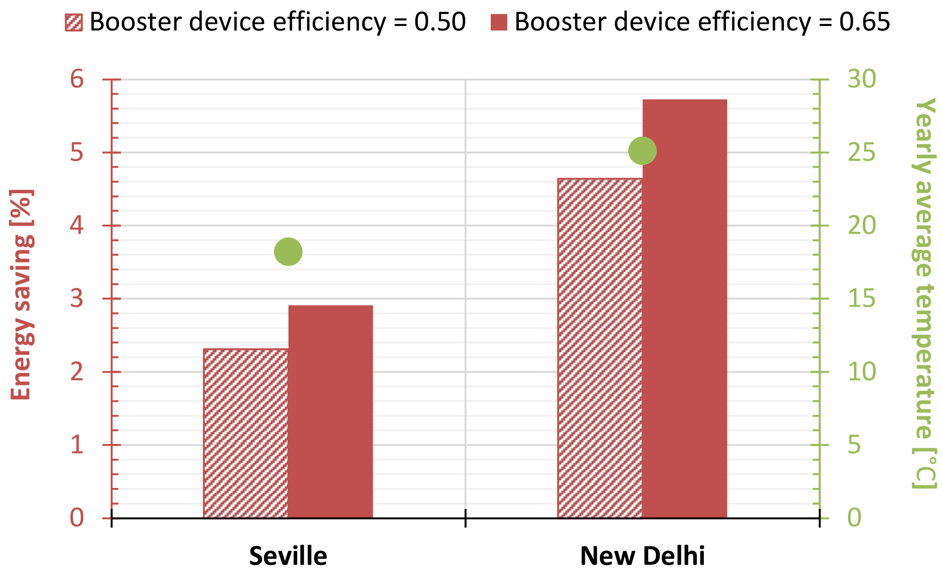

Figure 4: Energy savings (in %) offered by the supermarket refrigeration system with the new proposed technology (i.e., with the booster device) compared to the baseline in the selected locations

At a following step, an expander was also integrated into the system to take advantage of the increase available expansion work offered by the novel technology (Figure 5).

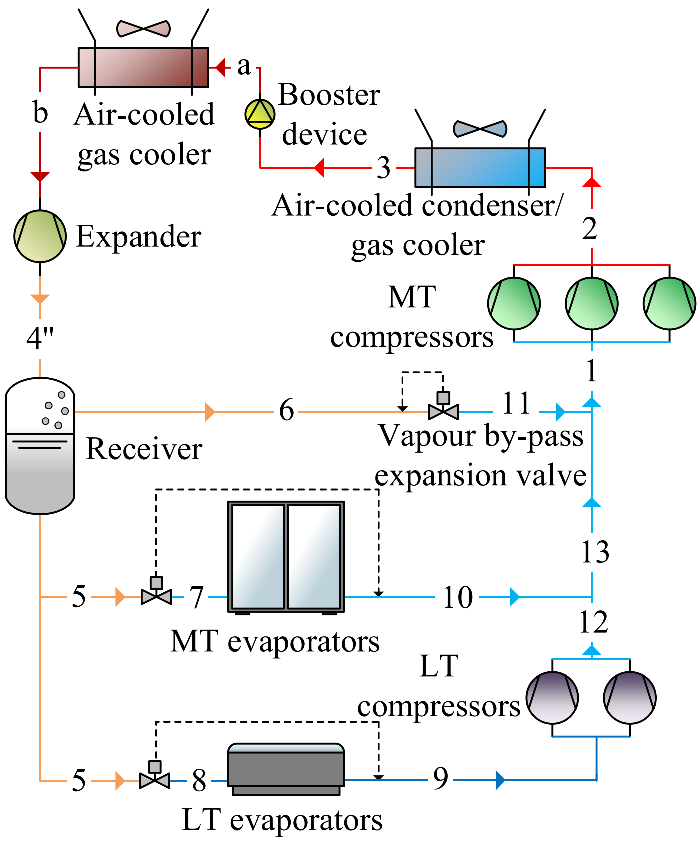

Figure 5: Schematic of the transcritical R744 supermarket refrigeration system with the new proposed technology (i.e., with the booster device) and an expander

The solution presented in Figure 5 was modelled using the same assumptions as the ones presented in Section 2 and the two additional assumptions listed below:

- the expander was activated only in transcritical regime, i.e., $t_{outdoor} \geq 23$ °C;
- the expander isentropic efficiency was calculated according to Eq. (4) (Zheng et al., 2025).

$$\eta_{expander} = 0.95 \cdot (0.7874 - 0.04196 \cdot \beta_{expander}) \qquad \text{Eq. (4)}$$

The results associated with the scenario based on the isentropic efficiency of the booster device of 0.65 and expander are summarized in Table 5. The COP values were observed to increase by from 8.5 % ($t_{outdoor}$ = 23 °C) to 22.5 % ($t_{outdoor}$ = 40 °C), highlighting the need to combine the proposed technology with an expander in transcritical R744 supermarket refrigeration systems at high outdoor temperatures.

Table 5. Optimal air-cooled gas cooler pressure for the supermarket refrigeration system with the new proposed technology (i.e., with the booster device) and an expander at different $t_{outdoor}$ ($\eta_{booster\ device}$ = 0.65)

$t_{outdoor}$ [°C]	23.00	25.00	30.00	35.00	40.00
Optimal air-cooled gas cooler pressure [bar]	72.33	82.33	110.00	126.33	130.00
COP [-]	2.46	2.33	1.97	1.67	1.42

As showed in Figure 6, the integration of the expander allowed obtaining energy savings by 7.80 % in Seville and 14.44 % in New Delhi compared to the baseline. The expander was found only to cover the power input required by the fans, thus dramatically limiting the energy benefits from the proposed solution. This was a consequence of the expander efficiency, reduction on the total R744 mass flow rate due to the air-cooled gas cooler and outdoor temperature trend in the selected locations.

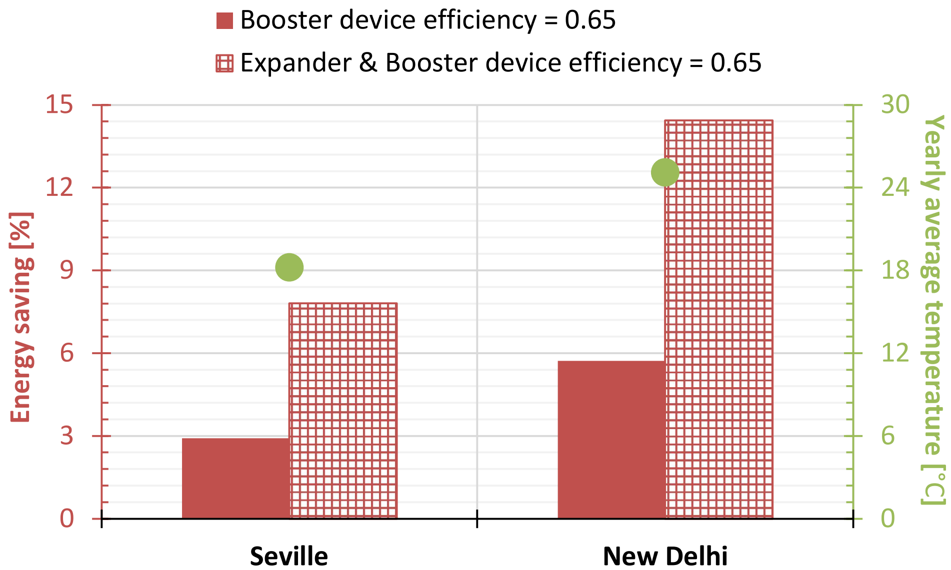

Figure 6: Energy savings (in %) offered by the supermarket refrigeration system with the new proposed technology (i.e., with the booster device) and expander compared to the baseline in the selected locations

3.3 Economic assessment

The economic assessment was carried out considering purchase equipment costs suggested by manufacturers of the sector. In particular, the purchase equipment cost of the booster device, the expander and the air-cooled gas cooler were considered equal to 15600 €, 9000 € and 7000 €, respectively.

The results obtained suggested that only the supermarket refrigeration system with the new proposed technology and an expander represents a reasonable investment.

Table 6. Additional investment recovery time (AIRT) (in year) for the supermarket refrigeration system with the new proposed technology (i.e., with the booster device) and with and without an expander in the selected locations

	Seville	New Delhi
AIRT of the system with the new proposed technology ($\eta_{booster\ device} = 0.65$) (in year)	10.3	10.0
AIRT of the system with the new proposed technology ($\eta_{booster\ device} = 0.65$) (in year)	8.2	8.1
AIRT of the system with the new proposed technology ($\eta_{booster\ device} = 0.65$) and expander (in year)	3.1	3.2

4 CONCLUSIONS

In this investigation a novel technology to adapt transcritical R744 supermarket refrigeration systems to warm and hot climates as well as to rising temperatures has been introduced. The new solution has been comprehensively studied from an energy and economic point of view considering two different locations, i.e. Seville (Spain) and New Delhi (India). The novel technology involves a booster device (increasing the R744 pressure) followed by an air-cooled gas cooler and installed between the conventional air-cooled condenser/gas cooler and high-pressure expansion valve.

The outcomes obtained have showed that energy savings by from 2.31 % to 2.91 % in Seville and from 4.64 % to 5.73 % in New Delhi can be attained with the aid of the novel technology. Therefore, the new solution has been combined with an expander replacing the high-pressure expansion valve, resulting in energy savings by 7.80 % in Seville and 14.44 % in New Delhi with an additional investment recovery time of about 3 years in both of the selected locations.

NOMENCLATURE

AEC	annual energy consumption (kWh/year)	AES	annual energy saving (%)
AIRT	additional investment recovery time (year)	c	average electricity cost (€/kWh)
CC	capital cost (€)	compr	compressor
COP	coefficient of performance (-)	ES	energy saving (kWh/year)
f_i	outdoor temperature bin	gc	gas cooler
GHG	greenhouse gas	GWP	global warming potential
LT	low temperature	MT	medium temperature
$\dot{Q}$	heat transfer rate (kW)	$\dot{W}$	power (kW)
β	pressure ratio (-)	Δ	increment
η	isentropic efficiency (-)		

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