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Semi-empirical analysis of HFC supermarket refrigeration retrofit with advanced configurations from energy, environmental, and economic perspectives

Analyse semi-empirique de la conversion des systèmes frigorifiques des supermarchés aux HFC avec des configurations avancées du point de vue énergétique, environnemental et économique

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ABSTRACT

F-gas phase-down schedules will remove most of the HFCs (hydrofluorocarbons) used in refrigeration systems in the short term. Besides refrigerant substitution, configuration modifications can be considered in existing installations to increase energy efficiency. Basic cycle, direct injection, economiser, parallel compression, and cascade configurations with internal heat exchanger have been proposed to increase the energy efficiency of a supermarket refrigeration system when replacing R-404A with R-449A at low and medium temperatures. Both systems are based on indirect expansion and are equipped with a subcooler. Their regular operation was recorded using R-404A and R-449A during a representative period. Then, a semi-empirical approach is followed to determine R-449A energy performance with each proposed configuration. Only parallel compression (PC) and basic cycle with internal heat exchanger (IHX) benefit energy performance, highlighting the medium temperature (MT) system. However, this benefit is not extended to the environmental analysis because the R-449A charge in PC significantly increases. Moreover, additional PC components extend the expected payback period, and a drop-in replacement is financially more interesting. Therefore, using R-449A with minor modifications in the MT and LT R-404A refrigeration system decreases 52% and 60% carbon footprint, respectively. The payback period of this action is below one year in both circuits. This study provides a semi-empirical methodology for existing systems to predict alternative refrigerants' energy performance.

1. Introduction

The Kigali Amendment to the Montreal Protocol (United Nations Environment Programme (UNEP), 2016) has established a phase-down schedule. Non-A5 countries have already started the hydrofluorocarbons (HFC) reductions, while A5 countries will start such decreases in the short term. The control of HFCs placed on the market and the gradual restrictions for refrigeration and air conditioning applications are motivating the European Union (EU) HFC phase-down (IIFIIR, 2020). On May 3, 2021, the United States Environmental Protection Agency (US EPA) published an F-gas Regulation draft, thus proposing to reduce the HFC production and consumption to 15% of the baseline by 2036 (Environmental Protection Agency, 2021).

R-404A is an HFC with a 100-year global warming potential (GWP_{100}) of 3922. As Calm (2008) predicted around 15 years ago, a new

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Nomenclature

COP	coefficient of performance (-)
CR	compression ratio (-)
E_{annual}	annual electricity consumption (kWh year^{-1})
h	specific enthalpy (kJ kg^{-1})
L_{anual}	annual refrigerant leakage (%)
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
n	lifetime of the installation (year)
N	compressor rotational speed (rpm)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
R^2	coefficient of determination (-)
SCD	subcooling degree (°C or K)
T	temperature (°C or K)
V_G	compressor displacement (m^3)

Subscripts

Disc	discharge
Iso	isentropic
K	condensation
O	evaporation
Ref	refrigerant
SC	subcooler
Suc	suction
Vol	volumetric

Greek

α	refrigerant recovered at the end of life (%)
β	carbon emission factor (CO_2-eq kWh^{-1})
Ρ	density (kg m^{-3})
Ε	heat exchanger effectiveness (-)
Η	compressor efficiency (-)

Abbreviatures

A5	Montreal Protocol Article 5
BC	basic cycle
CAS	cascade
CO_2-eq	carbon dioxide equivalent
DI	direct injection
ECO	economiser
EES	Engineering Equation Solver
F-gas	fluorinated gas
GWP	AR5 100-yr global warming potential
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HS	high stage (for the cascade configuration)
HTC	heat transfer coefficient
IE1, IE4	International Energy efficiency classes of electric motors
IHX	internal heat exchanger
LS	low stage (for the cascade configuration)
LT	low temperature
MT	medium temperature
PC	parallel compressor
SM	supermarket
TEWI	total equivalent warming impact
TXV	thermostatic expansion valve

generation of refrigerants with low GWP progressively replaces HFCs, including R-404A. McLinden et al. (2017) showed that only a few fluids possess the necessary combination of chemical, environmental, thermodynamic, safety properties, and trade-off relevance. The replacement of R-404A persists as one of the most critical challenges for the refrigeration industry. A few pure fluids present better energy performance than R-404A, but they are flammable and do not present similar operational characteristics (R-32, R-1270, R-1141 and R-1123) (Domanski et al., 2017). Several HFC/HFO (hydrofluoroolefin) mixtures have been proposed to replace this refrigerant with different system modifications (Heredia-Aricapa et al., 2020). However, the search for refrigerants that can optimise the balance of various refrigeration system properties, including environmental and safety characteristics, is still ongoing (Yang et al., 2021). Gao et al. (2021) considered that promising R-404A alternatives are already available, and HFC/HFO mixtures will be the main substitutes for R-404A in the future.

HFC/HFO mixtures that replace R-404A are grouped in low GWP but A2L or A1 but medium GWP alternatives. Therefore, contrary to mildly flammable low GWP HFC/HFO mixtures such as R-455A, R-454A, and R-454C (Mota-Babiloni et al., 2018; Oruç and Devecioğlu, 2021), R-448A and R-449A are non-flammable lower GWP refrigerants that are short term replacements to R-404A with comparable thermophysical properties (Mota-Babiloni and Makhnatch, 2021). The composition of both replacements is very similar (likewise occurred in the past for R-404A and R-507), R-448A composition is R-32/125/134a/1234yf/1234ze(E) (26/26/21/20/7 in mass%), and that of R-449A is R-32/125/134a/1234yf (24/25/26/25 in mass%), so conclusions obtained with these refrigerants are nearly exchangeable. R-448A and R-449A experimental energy and heat transfer performance have been compared with R-404A in a few previous articles.

Regarding studies focusing on energy efficiency and cold production, Deng et al. (2021) compared non-inverter and inverter cold storage units using R-404A and R-448A to reduce yearly energy consumption, life cycle cost and carbon footprint (3.0%, 2.7%, and 33.3%, respectively). Mota-Babiloni et al. (2015) measured between 6% to 21% higher coefficient of performance (COP) with R-448A than R-404A at low and medium temperature (LT and MT) conditions. Later, these results were used to develop a heat transfer model showing R-448A's evaporation effectiveness was 5% lower than R-404A (Mendoza-Miranda et al., 2016). In a previous investigation, Mota-Babiloni et al. (2014) proved that two-stage configurations (also known as advanced configurations) using lower GWP alternatives could overcome the R-404A basic stage COP. A prototype refrigerant mixture with a close composition to R-449A was also included.

Then, other previous studies are found concerning heat transfer studies for evaporation and condensation. Kedzierski and Kang (2016) determined that the local convective boiling heat transfer coefficients (HTC) for R-448A and R-449A are roughly 26 to 48% lower than R-404A under the studied case scenario. Lillo et al. (2019) attributed to the convective effect the higher R-448A flow boiling HTC measured at low vapour qualities compared to R-404A. Jacob et al. (2020) noticed slightly lower condensation HTC and 16% higher frictional pressure drop gradients for R-404A than R-448A at identical conditions. Jacob and Fronk (2021) developed a new heat transfer model for superheated and saturated condensation of HFC/HFO mixtures, including R-448A. Kim and Kim (2021a) compared R-448A and R-449A to long-term R-404A alternatives R-454C and R-455A in a 7.0 mm outer diameter microfin tube. They observed that the R-448A and R-449A lead to higher condensation HTC and smaller pressure drops. However, R-404A outperformed its alternatives because of a much lower temperature glide. Similar conclusions were obtained in another study regarding evaporation (Kim and Kim, 2021b), investigating the behaviour for a 5.6 mm inner diameter horizontal smooth tube. Lee et al. (2021) obtained comparable or higher HTC and pressure drop regarding the alternative

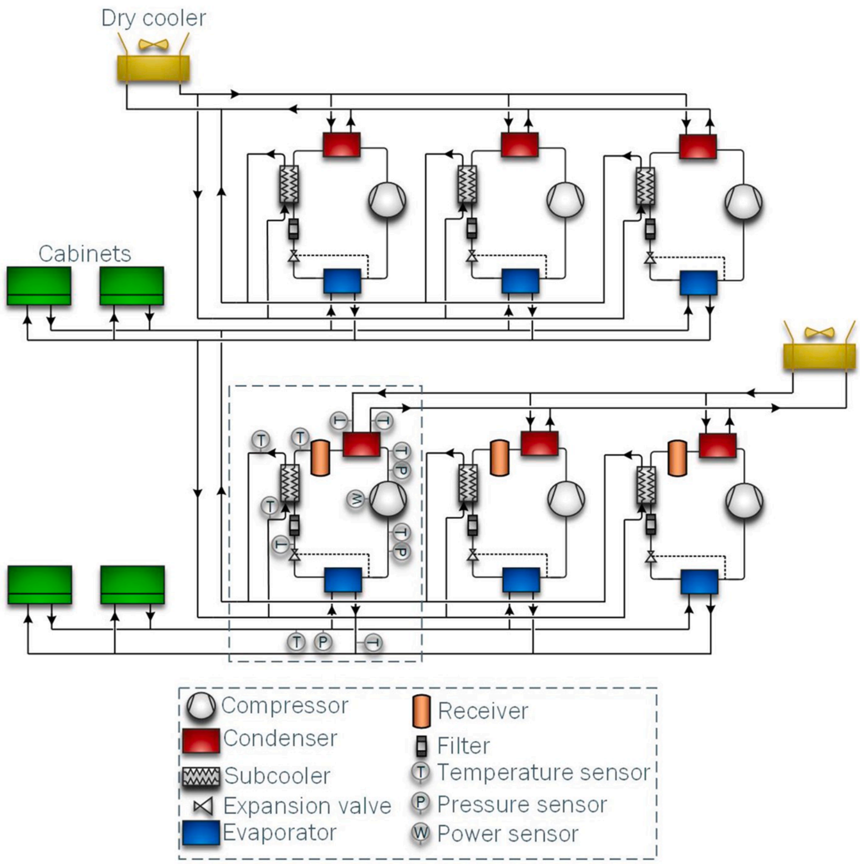

Fig. 1. Schematic of the baseline refrigeration system

refrigerants. Morrow et al. (2021) analysed the flow condensation correlations to identify their suitability to predict heat transfer performance of low GWP fluids, including R-448A and R-449A.

Citarella et al. (2022) concluded through a thermo-economic analysis that R-449A performs better as a mid-term scenario refrigerant in the European market for a 2.5 kW commercial refrigeration unit. However, scarce information can be found in the literature about the accurate behaviour of this fluid when replacing R-404A. Field test measurements provide reliable and valid conclusions about refrigeration system operation and energy performance when working with novel future-proof refrigerants (Sawalha et al., 2017). Makhnatch et al. (2017) and Makhnatch et al. (2018) proved how the R-449A used instead of R-404A resulted in a higher energy efficiency of refrigeration systems installed for food preservation and freezing in a supermarket refrigeration system with a subcooler. However, the information provided by field test measurements can be extended, for instance, to predict the energy performance in other configurations with higher accuracy than theoretical analysis and a lower cost than experimental studies. Typically, new configurations in supermarkets are theoretically compared with the HFC baseline (Sharma et al., 2014).

This article comprehensively studies advanced configurations intending to increase the energy, environmental and economic indicators when utilising R-449A in R-404A indirect supermarket refrigeration systems with a subcooler. A semi-empirical methodology for predicting and validating the performance of advanced configurations in existing refrigeration systems with minimum measurements (minimal supermarket modifications) is proposed, including the estimation of compressor efficiencies and subcooler heat transfer. The results are used to obtain the associated energy, environmental, and economic impacts and compare them with R-404A and R-449A direct measurements.

2. Baseline supermarket refrigeration system

This study focuses on a semi-empirical assessment of a supermarket retrofit with advanced configurations and alternative refrigerants. A supermarket located in Södertälje (south-central part of Sweden, latitude of 59.2°N) is used as the reference for the calculations. The supermarket comprises medium temperature (MT) and low temperature (LT) indirect expansion refrigeration systems connected in parallel, as indicated in Fig. 1. An intermediate fluid (water/propylene glycol mixture, 62/38 vol% for MT and pumped CO_2 for LT) is used as a heat transfer medium between the main refrigeration circuit and the cabinets. Meanwhile, the heat transfer fluid between the main refrigeration circuit and dry cooler is water. Contrary to the MT system, the LT system has a liquid receiver.

Further details about the operation and performance of the MT and LT circuits of the baseline system are studied in Makhnatch et al. (2017) and Makhnatch et al. (2018), respectively. Additional detailed information about the system and components characteristics, operation, and measurements can be consulted in the open-access report of Rogstam et al. (2016). This document explains in detail how R-449A was used in the R-404A system with minor system modifications (charge optimisation and expansion valve adjustment), following the so-called drop-in replacement procedure.

3. Proposed configurations for increasing energy efficiency

Several configurations have been proposed to increase the refrigeration system's energy performance, reducing lifetime cost and carbon footprint. Proposed configurations are schematically represented in Fig. 2, modelled as indicated in Mateu-Royo et al. (2021). All arrangements include a subcooler to increase the evaporator's refrigerating effect. Similarly, an internal heat exchanger (IHX) is considered in all

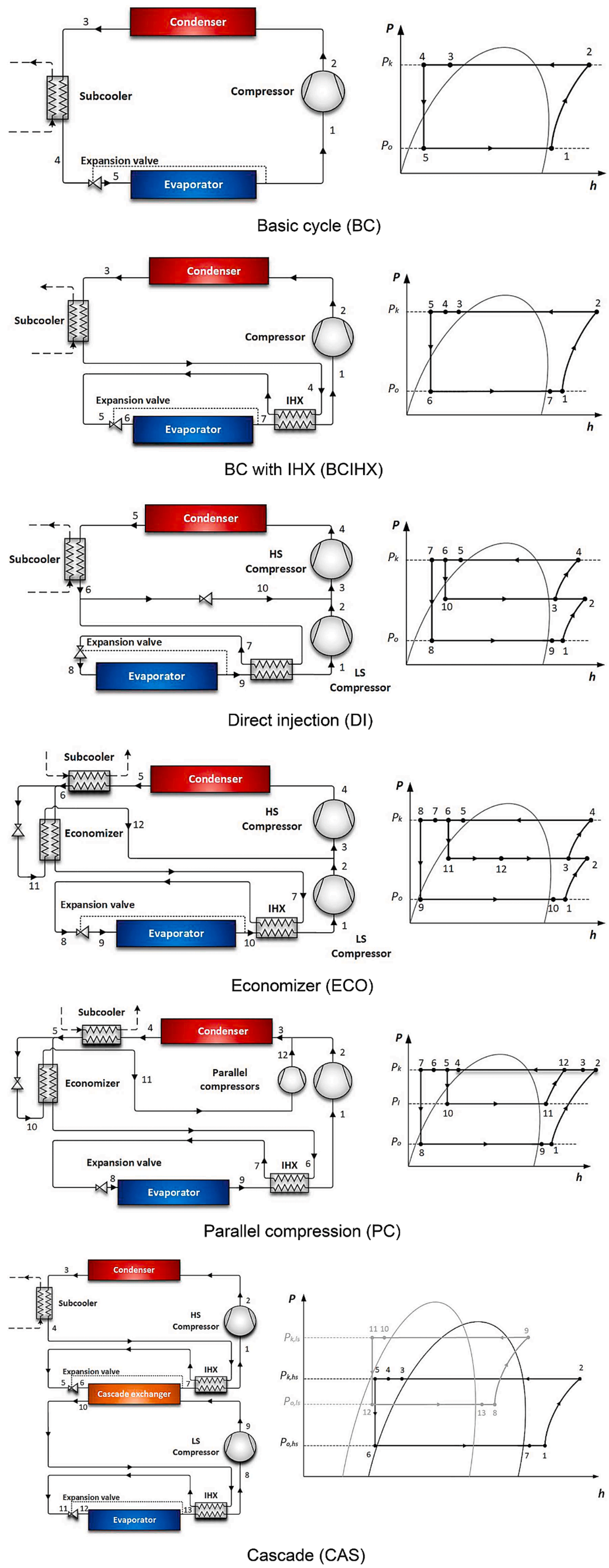

Fig. 2. Schematic representation of the configurations

Table 1
Operating conditions according to actual supermarket operation

Parameters	MT circuit	LT circuit
Middle evaporating temperature [°C]	−20 and −10	−40 and −30
Middle condensing temperature [°C]	25 and 40	20 and 40
Total superheating degree [K]	7	10
Condenser subcooling degree [K]	0	0
Subcooler subcooling degree [K]	2	SCD=f($\dot{Q}_{SC}$)[a]

[a] Discussed in Section 4.3.

configurations to increase energy efficiency. Its heat transfer effectiveness is controlled to avoid extreme compressor discharge temperature not recommended by compressor manufacturers (105°C in regular operation and 120°C peak). In the following, the main characteristics of each configuration are exposed.

Basic cycle (BC) with subcooler is used as a baseline for comparison. It consists of a compressor, an expansion valve, a condenser, an evaporator, and a heat exchanger that acts as a subcooler. Besides, the basic cycle with IHX (BCIHX) adds another heat exchanger that thermally connects suction and liquid lines. By subcooling the liquid entering the expansion valve, inlet evaporator vapour quality (and specific enthalpy) is lower, thus increasing refrigerating effect. On the other hand, as the suction temperature increases, so does the discharge temperature. Therefore, the variation in the COP depends on the refrigerant and operating conditions.

In the direct injection with IHX (DI) cycle, the compression is separated into two stages in series, reducing the pressure ratio on each compressor. A fraction of refrigerant mass flow rate is expanded at an intermediate pressure and mixed with the low-stage compressor discharge. The resulting vapour is desuperheated, and consequently, the suction and discharge temperature in the high-stage compressor is decreased. On the other hand, the mass flow rate through the high-stage compressor is increased.

The economiser with IHX (ECO) cycle uses an additional heat exchanger (economiser) and keeps the intermediate direct injection of the previous cycle. The economiser subcools refrigerant before it is expanded to a low pressure using refrigerant at an intermediate pressure.

The parallel compression with IHX (PC) adds a parallel compressor and economiser to the BCIHX configuration. Refrigerant expanded to an intermediate pressure is evaporated in the economiser and introduced into a smaller additional parallel compressor that shares discharge with the main compressor, which receives refrigerant from the evaporator.

The two-stage cascade with IHX (CAS) cycle combines two basic cycles with an intermediate heat exchanger (named cascade heat exchanger), which serves as an evaporator for the high-stage cycle (R-449A), and as a condenser for the low-stage cycle (R-744).

4. Model and assumptions

4.1. Conditions for the selection of the configuration

Two representative temperature lifts have been proposed following the operational analysis of a supermarket refrigeration system performed in Makhnatch et al. (2017) and Makhnatch et al. (2018), Table 1.

Representative measurements and calculated energy parameters are shown in Annex I to give an insight into the operation of the baseline circuits. The following sections use these measurements to determine the new configurations' energy, environmental and economic values.

As an existing installation, the mass flow rate of the supermarket refrigeration main or secondary circuits was not directly measured because flow meters would imply a modification of the original system. Therefore, other methodologies must be considered for determining this parameter in existing installations with minor human intervention.

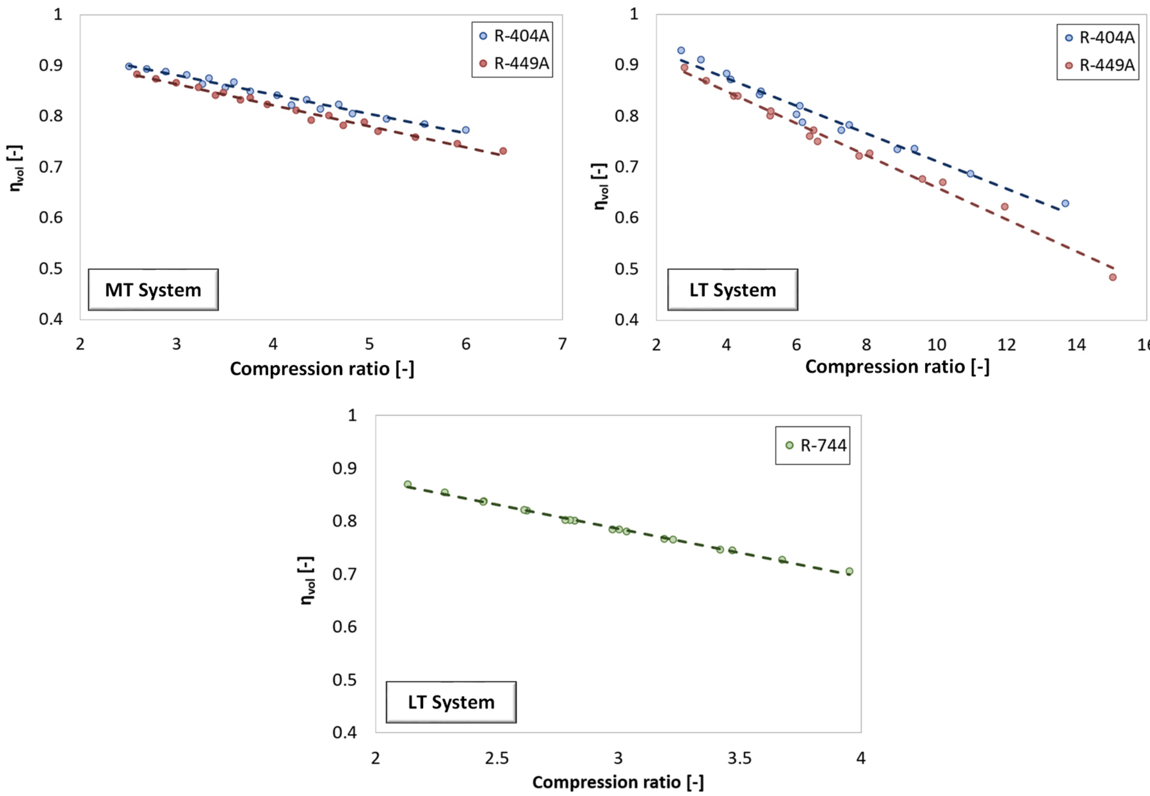

Fig. 3. Compressors volumetric efficiency

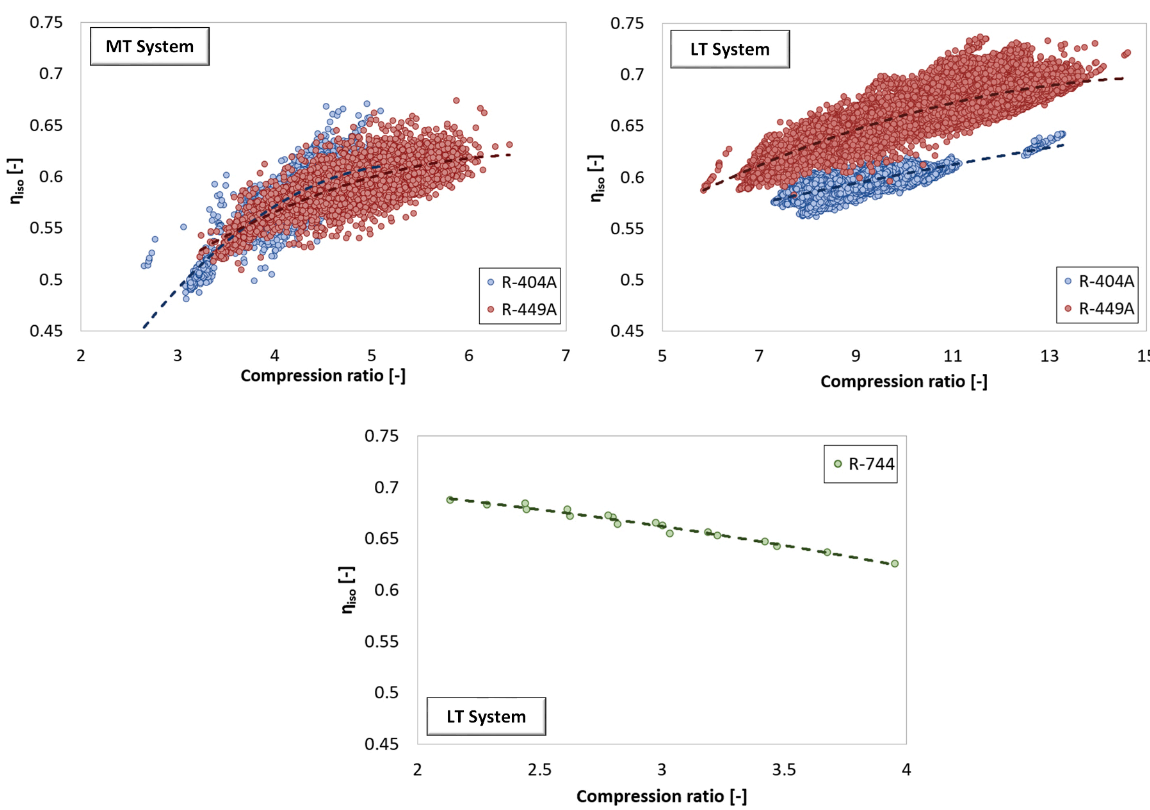

Fig. 4. Compressors isentropic efficiency

Table 2
Summary of polynomial equations describing compressor efficiencies

System	R-449A	R-404A
MT	$\eta_{vol} = -0.0412CR + 0.9865$	$\eta_{vol} = -0.0379CR + 0.9944$
	$\eta_{iso} = -0.0079CR^2 + +0.105CR + 0.2718$	$\eta_{iso} = -0.0213CR^2 + + 0.2293PR - 0.0045$
LT	$\eta_{vol} = -0.0313CR + 0.9741$	$\eta_{vol} = -0.0271CR + 0.9835$
	$\eta_{iso} = -0.0011CR^2 + + 0.0353CR + 0.419$	$\eta_{iso} = -0.0002CR^2 + 0.0124CR + 0.4965$
	$\eta_{iso,R-744} = -0.0046CR^2 - 0.0073CR + 0.7253$	

For the electromechanical efficiency of the compressors, the minimum values of the IE4 class have been chosen for the motor. Note that 2- and 4-pole low-voltage three-phase motors till 1 MW are categorised from IE1 to IE4, being IE4 the highest efficiency. Thus, the MT and the LT compressors have considered electromechanical efficiency of 0.94 and 0.92 (including R-744).

4.2. Compressor efficiencies

Representative semi-hermetic reciprocating compressors with characteristics like those used in the baseline MT and LT systems have been selected to retrieve the necessary information for volumetric efficiency (BITZER Kühlmaschinenbau GmbH, 2020). Considering the conditions listed in Table 1, the compressor used for the MT system is the Bitzer 6FE-50Y, whereas the LT compressor is the Bitzer 4GE-23Y. On the other hand, the compressor selected for the simulation of the R-744 low-stage in the cascade configuration is the Bitzer 4ESL-9K-40S, chosen according to the LT maximum cooling capacity.

The volumetric efficiency of the selected compressors was obtained by comparing the mass flow rate provided by the compressor manufacturer with theoretical values taking unitary volumetric efficiency, Eq. (1) and (2). The resulting regressions and compressor manufacturer data are shown in Fig. 3, particularised for each refrigerant and system.

$$\eta_{vol} = \frac{\dot{m}_{ref,manufacturer}}{\dot{m}_{ref,theoretical}} \tag{1}$$

$$\dot{m}_{ref,theoretical} = V_G \frac{N}{60} \rho_{suc} \tag{2}$$

Contrary to the volumetric efficiency, the isentropic efficiency of MT and LT compressors has been based on direct measurements. Therefore, direct R-404A and R-449A temperature and pressure measurements at the compressor's suction and discharge have been used to determine the enthalpy through Engineering Equation Solver (EES) (S.A. Klein, 2019). These values are then used in the isentropic efficiency equation, Eq. (3). The isentropic efficiency of the R-744 compressor in the low stage of CAS is based on compressor manufacturer data. Fig. 4 shows the obtained isentropic efficiency values and regressions.

$$\eta_{iso} = \frac{h_{disch,iso} - h_{suc}}{h_{disch} - h_{suc}} \tag{3}$$

The volumetric efficiency of the R-404A compressor is comparable or higher than that of R-449A in both systems. The isentropic efficiency is slightly higher in the MT system, being around 2% the maximum difference with the regression. The compressors present a higher efficiency

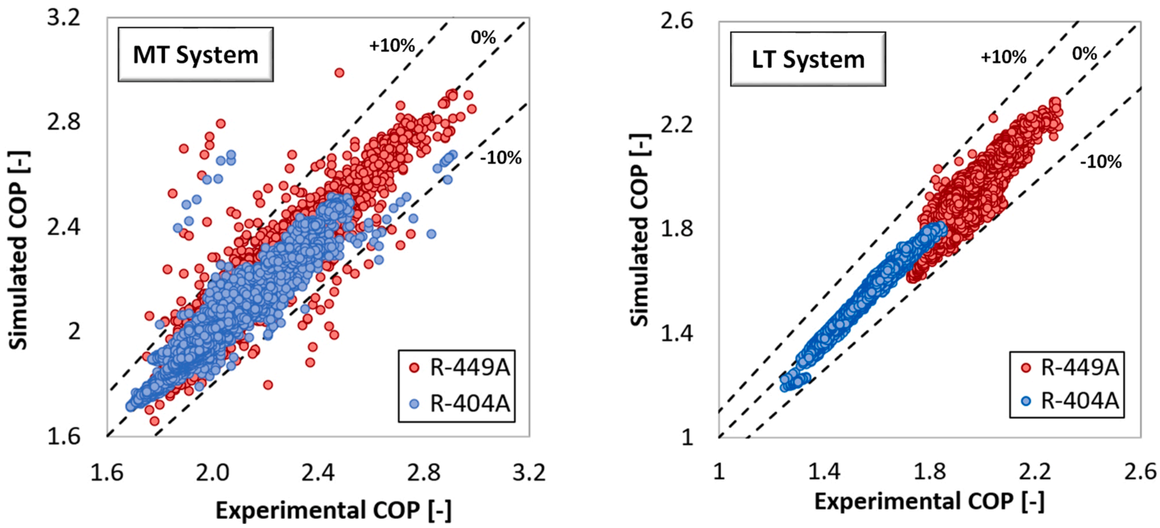

Fig. 5. COP deviation between measurements and the model

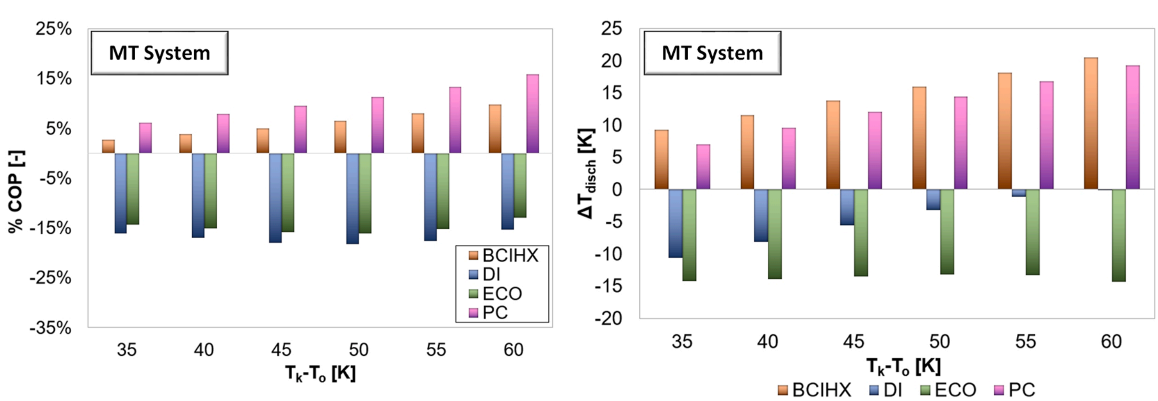

Fig. 6. COP and discharge temperature deviation between MT baseline and advanced configurations

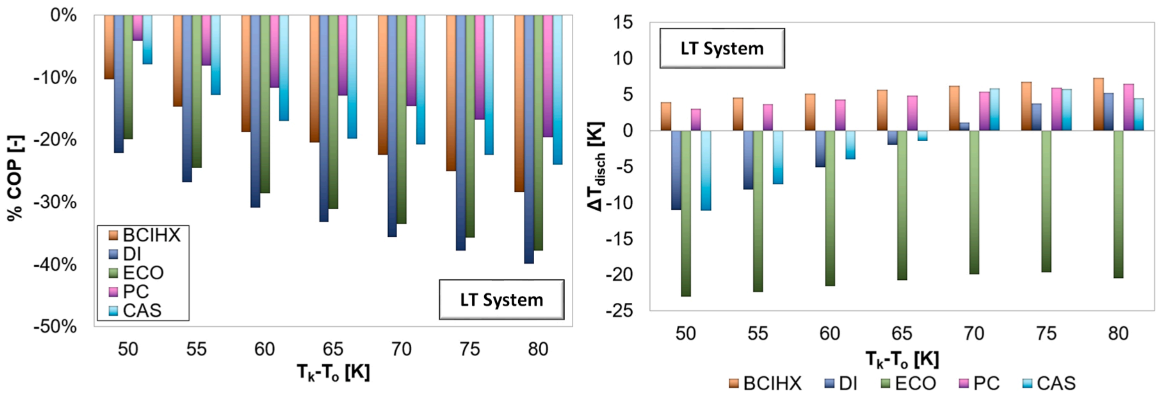

Fig. 7. COP and discharge temperature deviation between LT baseline and advanced configurations without subcooler

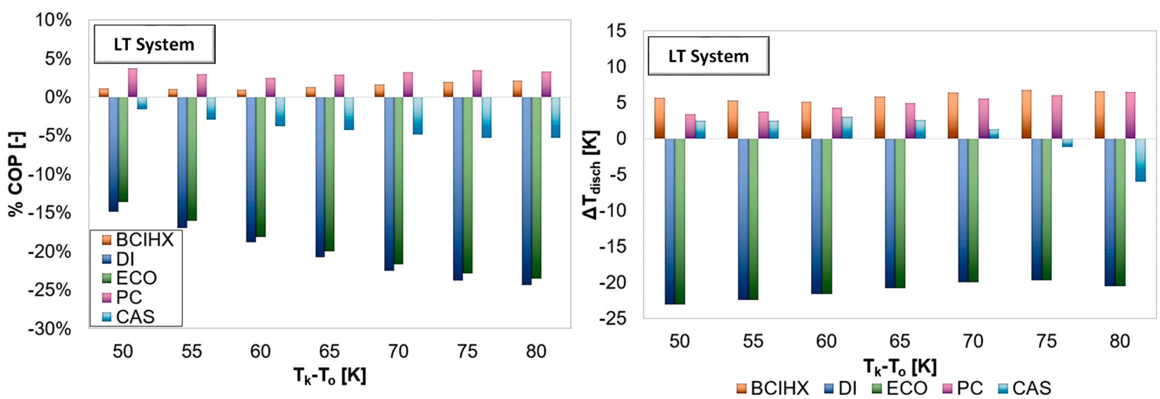

Fig. 8. COP and discharge temperature deviation between LT baseline and advanced configurations with subcooler

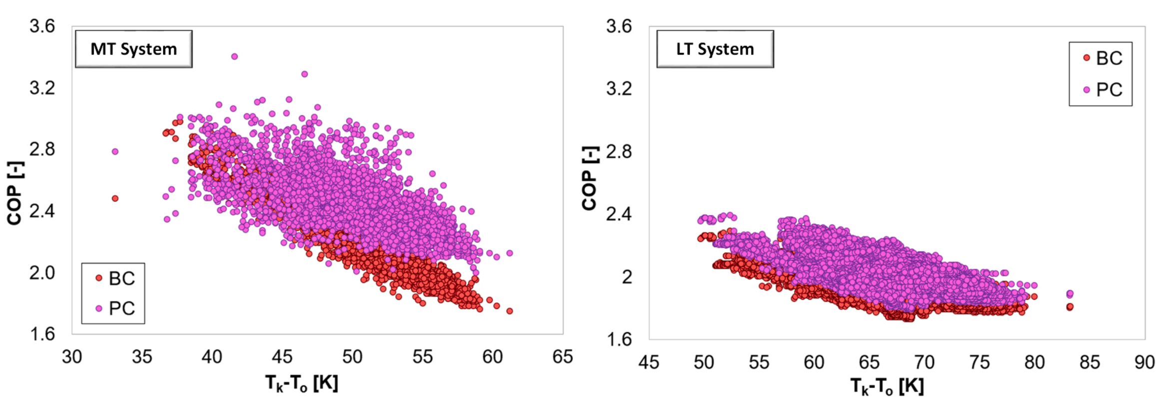

Fig. 9. R-449A COP measured in the supermarket refrigeration system and obtained with the PC semi-empirical approach

in the LT system at higher compression ratios. The isentropic efficiency of R-449A is between 1.5% and 7% higher than R-404A. Moreover, the R-744 compressor has higher isentropic efficiency for lower compression rates. Compressor efficiencies correlations resulting from this analysis are summarised in Table 2.

Other methodologies recently proposed for reciprocating compressor modelling can be found in (Belman-Flores et al., 2015; Roskosch et al., 2017.

4.3. LT subcooling

A correlation is necessary to determine the subcooling degree caused by the subcooler in the LT system, given the significant variation observed in previous studies. Since the heat transfer fluid temperature is unavailable, the second-degree multivariate regression has been based on the refrigerant mass flow rate, Eq. (4). The regression model is characterised by an R^2 of 0.73, which is considered sufficient because it is based on on-site measurements with limited modifications. Note that $T_{SC_{ref,inlet}}$ is the refrigerant temperature at the inlet of the subcooler, and it is assumed the same as the condenser outlet.

$$\dot{Q}_{SC} = 245.01\dot{m}_{ref}{}^2 - 2.097\cdot10^{-3}T^2_{SC_{ref,inlet}} + 2.126T_{SC_{ref,inlet}}\dot{m}_{ref} - 78.67\dot{m}_{ref} + 0.0517T_{SC_{ref,inlet}} + 3.732 \quad (4)$$

4.4. IHX effectiveness

In each configuration, the effectiveness of heat exchangers (econo-

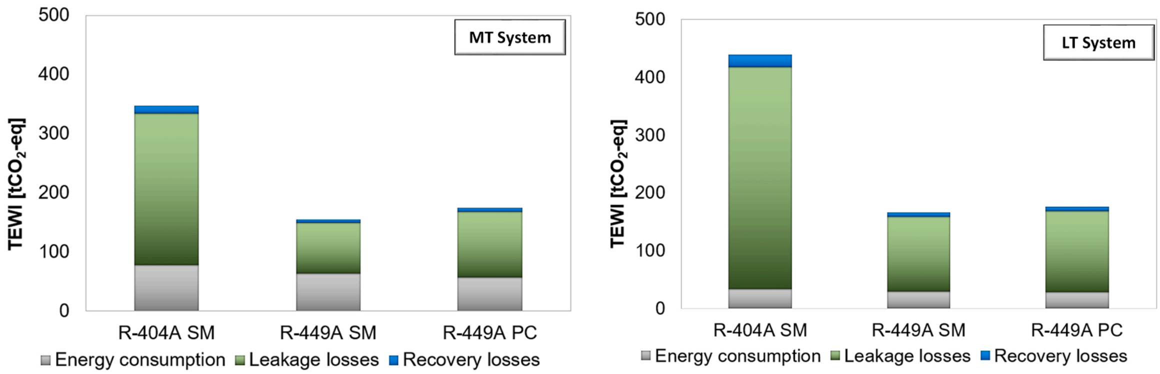

Fig. 10. TEWI for the baseline system with R-404A and R-449A and the proposed PC configuration

miser and internal heat exchanger), Eq. (5), is based on the Golden Section Search algorithm implemented in EES to increase COP while keeping compression discharge temperature below a certain threshold at 95% of operation time. Selected values for the IHX effectiveness are mentioned in the results section when required.

$$\varepsilon_{IHX} = \frac{\dot{Q}_{actual}}{\dot{Q}_{maximum}} \tag{5}$$

The methodology followed in this paper is summarised in Annex II.

5. Results

5.1. Model validation

The accuracy of the developed model was compared with the measured data. As a result, most of the points obtained with the model within ±10% deviation compared with experimental data (Fig. 5).

5.2. Results for configurations in MT conditions

The potential for increasing refrigeration system energy efficiency (expressed by COP variation) was analysed by comparing the COP of the baseline system (basic cycle with subcooler configuration) with that resulting in advanced configurations over a range of temperature lifts (temperature difference between evaporator and condenser).

Fig. 6 compares both COP and compression temperature discharge deviation from the baseline system. Following the optimisation procedure with the discharge temperature limitations, heat exchanger effectiveness for the IHX of BCIHX is 0.4, and the rest of the configurations and heat exchangers were set to 0.8.

Fig. 6 proves that the COP for BCIHX and PC configurations is up to 7% and 15% higher than the baseline configuration. However, the rest of the arrangements result in a COP decrease. The experimental compressor isentropic efficiency does not benefit from reducing the pressure ratio given (Fig. 4). Furthermore, the benefits of two-stage advanced configurations (lower superheating degree) do not overcome the existing caused by a subcooler and IHX. As Oruç and Devecioğlu (2020) concluded, retrofitting a refrigeration system with an IHX with a high area (plate heat exchanger) increases the COP.

As Fig. 6 suggests, the temperature increase caused by the IHX is not excessive, so the compressor does not reach dangerous temperatures for its regular operation. The increase in discharge temperature is between 9 and 20 K for BCIHX and 7 and 19 K for PC. Discharge temperature is reduced in two-stage configurations (f.i., by 14 K in economiser configuration), but energy efficiency is not noticeably increased. Therefore, an IHX or PC retrofit is recommended for the MT system.

5.3. Results for configurations in LT conditions

Extra cooling provided by the LT subcooler comes from the MT system. If the LT subcooler is removed, it could lower cooling capacity and, therefore, the electricity consumption of the MT system. Thus, the practical suitability of the subcooler in the LT system must be studied with the new configurations.

Firstly, the advanced configurations are analysed without a subcooler. In this case, the IHX effectiveness was set to 0.1 for BCIHX, 0.2 for PC, 0.25 for the high-stage of CAS. For the rest of the configurations and heat exchangers, 0.8. The intermediate temperature of CAS was set at –20°C from 50 to 60°C temperature lift and –10°C for the rest of the conditions. The results are summarised in Fig. 7.

The removal of subcooler in advanced configurations in the LT circuit decreases COP in all cases. The decrease is more considerable for higher temperature lifts, where the benefit of the subcooler in the baseline configuration is higher. Configurations with higher COP are BCIHX and PC, although still not acceptable in practical terms. The increase in discharge temperature is only moderate (up to 7 K).

The comparison is performed again but includes the subcooler in the advanced configurations in the position shown in Fig. 2. COP and discharge temperature variations of advanced configurations with IHX are shown in Fig. 8. In this case, the IHX effectiveness was limited to 0.25 for BCIHX, and 0.3 for PC. For the rest of the configurations and heat exchangers, 0.8. The intermediate temperature of the CAS configuration was set at –20°C.

As shown in Fig. 8, the analysed modifications could not significantly increase the energy efficiency of the baseline system under all LT temperatures considered here. Marginally better results are obtained with BCIHX and PC, increasing COP up to 4%. Besides, DI and ECO decrease the COP down to approximately 24%, whereas the CAS maximum decrease is 5%. As observed for the MT system, two-stage LT configurations present lower COP than single-stage cycles. This reduction is due to the isentropic efficiency of the compressors, which decreases far from the nominal operation. As the IHX effectiveness is lower in this system, the discharge temperature increase of the BCIHX and PC configurations is only 7 K. Moreover, given the higher pressure ratios of the LT system, the discharge temperature decrease caused by the two-stage configurations is noticeable.

Already existing external subcooling also considerably increases the COP of advanced configurations. However, the resulting benefit depends on the configuration due to the refrigerant properties entering the subcooler.

The results presented for MT and LT systems point out the parallel compression configuration (PC) as the best alternative to increase the energy performance of the baseline system. Therefore, the PC is the advanced configuration selected to determine the supermarket refrigeration system's potential energy, environmental, and economic improvement.

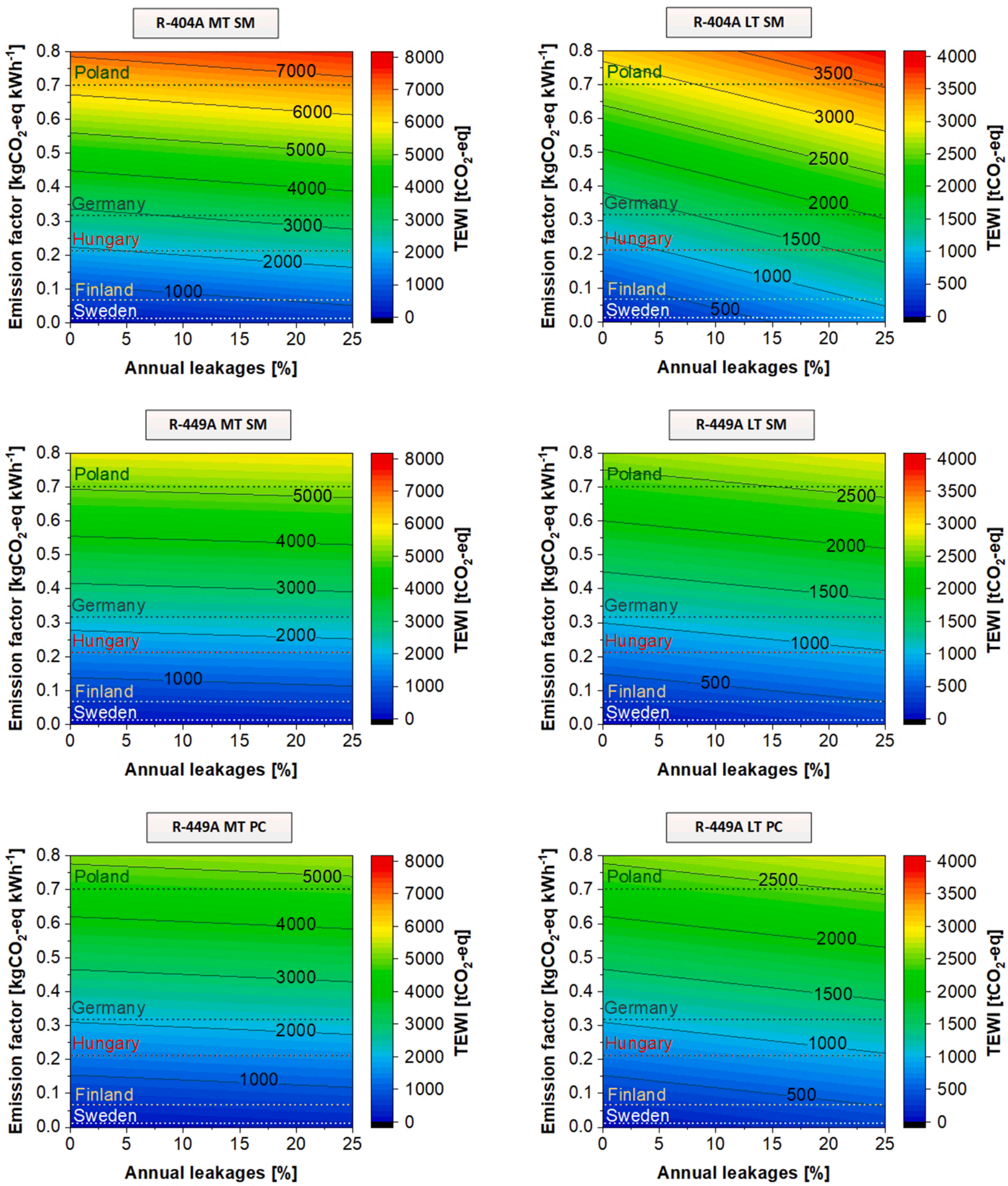

Fig. 11. TEWI for different annual leakages and carbon emission factors

Table 3
Budget for the MT PC system retrofit

Quantity	Component	Description	Unitary cost (€)	Total cost (€)
3	Parallel compressor	Bitzer 4NES-14Y	5903	17709
3	Economiser	SWEP F85 × 12	257	771
3	IHX	SWEP B15Tx49/2P	225	675
3	TXV	Danfoss TGE-10-11	236	708
3 × 1 m	Additional pipelines	1-3/8'' x 1.25	28	84
48.45 kg	Refrigerant	R-449A	65	3149
16h x 2	Labour costs		20	640
Total cost				23736

Table 4
Budget for the LT PC system retrofit

Quantity	Component	Description	Unitary cost (€)	Total cost (€)
3	Parallel compressor	Bitzer 4CES-9Y	4185	12555
3	Economiser	SWEP F85 × 6	194	582
3	IHX	SWEP Bx4TMx14	80	240
3	TXV	Danfoss TGE-10-11	236	708
3 × 1 m	Additional pipelines	1-3/8'' x 1.25	28	84
60,84 kg	Refrigerant	R-449A	65	3954
16h x 2	Labour costs		20	640
Total cost				18763

5.4. Energy semi-empirical comparison

The simulation was further applied to predict the PC system energy performance compared to real operation. All experimental temperature measurements in the baseline system are used as input parameters for R-449A PC semi-empirical calculations. The comparison presented here is performed at constant cooling capacity. Thus, the power consumption of the semi-empirical compressor is used to determine the COP. Fig. 9 reflects the results of the COP obtained with a PC in all measured conditions using R-449A.

For MT, the COP obtained for PC averages 2.42, compared to 2.16 for the baseline (BC); it approximately represents a 12% increase. The COP obtained for the LT PC system is 2.17 on average, compared to 2.10 obtained with the baseline configuration. Hence, the average increase is only 3.3% in this system. This analysis agrees with the previous discussion, where the PC and BC systems were compared at limited operating conditions.

From an energy point of view, retrofitting the baseline system to a PC could be beneficial, particularly at MT conditions. However, including new components can increase the required refrigerant charge and affect carbon footprint and economic analysis.

5.4. Environmental comparison

Once the energy benefit is proved in both systems with the PC configuration using R-449A, the CO_2-eq emissions were calculated following the total equivalent warming impact (TEWI) methodology, Eq. (6).

$$TEWI = GWP\ m\ L_{annual}\ n + GWP\ m\ (1-\alpha) + n\ E_{annual}\ \beta \tag{6}$$

The GWP values are 3943 for R-404A and 1282 for R-449A (AR5, (Myhre et al., 2013)). An annual leakage percentage of 12% has been assumed. The lifetime is 15 years, and the end-of-life losses are 0.1 (α of 0.9). These values have been taken from the International Institute of Refrigeration guidelines (IIR LCCP Working Group, 2016). The refrigerant charge initially used for both fluids was measured in one circuit. They are multiplied by the number of circuits to obtain the total refrigerant charge in the baseline case. Therefore, the MT and LT systems are charged with 36 and 54 kg for R-404A and 37.5 and 56.25 kg for R-449A.

On the other hand, the refrigerant charge required by additional PC heat exchangers is determined using plate heat exchanger manufacturer data, and 1 m extra liquid lines are considered per circuit. Thus, the PC MT and LT systems require 61.2 and 65.7 kg of R-449A (63% and 17% increase in refrigerant charge, respectively).

For the indirect emissions, the average carbon emission factor for Sweden has been considered (EEA, 2022). Finally, the annual energy consumption value has been extrapolated from the point-by-point

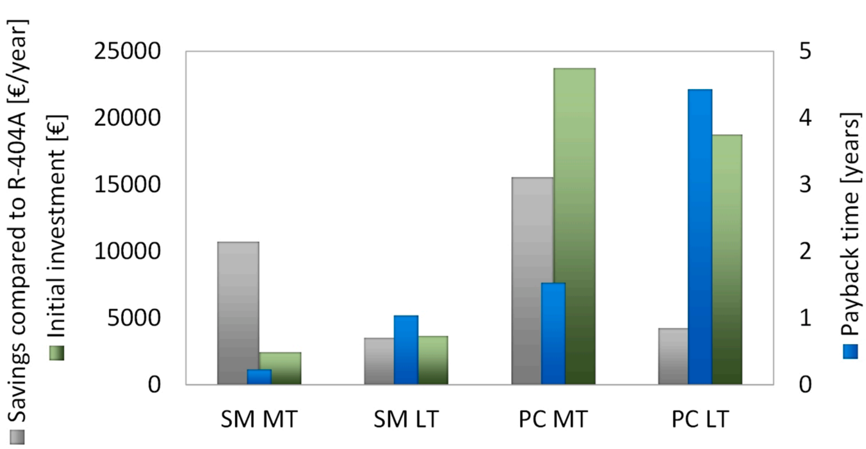

Fig. 12. Financial analysis of am R-449A drop-in and PC retrofit in an R-404A supermarket refrigeration system

measurements (baseline) or semi-empirical calculations (PC).

Fig. 10 shows the carbon footprint emissions calculated with the TEWI methodology for the different scenarios (Mota-Babiloni et al., 2020). Simply replacing R-404A with R-449A implies a notable difference in the resulting CO_2-eq emissions. With the current configuration and R-449A (noted as SM in the figures), an approximate 15-years reduction of 200 tCO_2-eq is achieved. However, this reduction is less significant with the PC configuration, approximately 150 tCO_2-eq. It is due to a more substantial influence of refrigerant leakage than the energy consumption reduction.

As in the MT system, replacing R-404A with R-449A in the LT system results in notable carbon emission reductions, 270 tCO_2-eq in the case of drop-in substitution, and 10 tCO_2-eq less with the PC retrofit. However, the PC configuration would also cause a slight increase in the carbon footprint impact compared to the direct replacement with R-449A because of the increase in the refrigerant charge.

Despite the energy benefit produced by the new configuration, having a carbon emission factor relatively small (compared to other European countries) highlights the impact of refrigerant charge and GWP. Therefore, carbon emission factor and leakage ratio are varied in a carbon footprint sensitivity analysis. Results are shown in Fig. 11, where carbon emission factors of other European cold countries such as Finland, Hungary, Germany, and Poland were compared to Sweden (EEA, 2022).

When higher emission factors (Poland) and annual leakages (25%, maximum for indirect refrigeration) are considered, carbon emissions in the R-404A MT and LT systems are around 40% higher than R-449A drop-in and PC. Considering the MT system and the carbon emission factor of Hungary, the PC is already competitive. However, R-449A drop-in and PC depict comparable TEWI evolution for the LT system, and slight benefits are only observed in countries with a carbon emission factor above the German one. Another difference is that the reference lines inside the contour plot have a higher slope for the LT system. Hence, refrigerant leakage has more influence than the MT system, which is more affected by the indirect emissions. Therefore, stricter leakage control is necessary for LT systems to reduce resulting carbon emissions. It can be concluded that the best solution from an environmental perspective depends on the leakage profile and the country where the installation is located. Systems in Sweden require solutions with minimum GWP or charge reduction strategies.

5.5. Economic comparison

Finally, an economic analysis complements this study. The approximate cost of components included in the PC configuration is shown in Table 3 and Table 4. Additional parallel compressors have been selected according to the calculated displaced volume. The electricity cost is based on the price in Sweden, 0.095 € kWh^{-1}, retrieved from the Eurostat database (Eurostat, 2021).

Then, this information is used to determine the financial viability of the R-404A replacement. Fig. 12 demonstrates how the R-404A replacement with R-449A provides a fast return since the annual electricity consumption is highly decreased. The payback period for the R-449A PC is more prolonged than drop-in replacement because the initial investment is higher, but R-449A PC provides higher savings, particularly for the MT system. Considering a 15-years lifetime, PC would result in 32% higher savings in the MT system but 9% lower in LT.

6. Conclusions

This paper proposed a semi-empirical analysis based on field test measurements performed in an R-404A MT and LT supermarket refrigeration systems with a subcooler. It aims to predict a system redesign's energy, environmental and economic effects using R-449A advanced vapour compression configurations and determine the main factors influencing viability.

The considered R-449A configurations compared to the baseline system (R-449A basic cycle with subcooler) are basic cycle, direct injection, economiser, parallel compressor, and two-stage cascade, all with IHX and subcooler. Direct measurements are used to determine the simulations' input conditions for both circuits and compressor efficiencies.

The MT system is more benefitted by BCIHX and PC configurations, which have lower IHX effectiveness. For LT, the energy benefit is not so evident with these configurations. The rest of the arrangements do not improve the baseline's COP, caused mainly due to the compressor efficiency reduction when the prevailing operation conditions shift away (lower pressure ratio with two-stage configurations) from those optimal for a given compressor. Besides, it has been proved that the subcooler in LT increases COP significantly, even for the advanced configurations.

Despite having energy benefits with R-449A PC configuration, it does not overcome those obtained with a simple drop-in R-404A replacement with R-449A. Sweden's low carbon emission factor makes direct emissions predominant in the resulting TEWI values. Then, the payback period of an R-404A drop-in replacement substitution is significantly small, so economic savings with PC configuration are only evident for the MT system.

This paper provides a methodology for studying an HFC substitution in refrigeration systems in operation with only simple measurements (pressure and temperature). A complete analysis and modelling of the system are necessary to determine the impact of modifications accurately. Other compressors with different or more advanced technology could be integrated into the model, with the subsequent reduction in energy consumption. Moreover, the benefit of the subcooler and the impact of the refrigerant charge in advanced configurations have been proved. Therefore, this work could continue, including semi-empirical analysis with refrigerants with GWP below 150 and other countries with intermediate carbon emission factors. Another way to extend the conclusions is following Life Cycle Climate Performance or Life Cycle Assessment methods for the environmental analysis instead of TEWI.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex I. Summary of R-404A and R-449A measurements

As indicated in the text, representative measurements and calculated energy parameters are shown in Fig. AI.1 to give an insight into the operation of the baseline circuits. This figure summarises R-404A and R-449A operations without consulting previous papers.

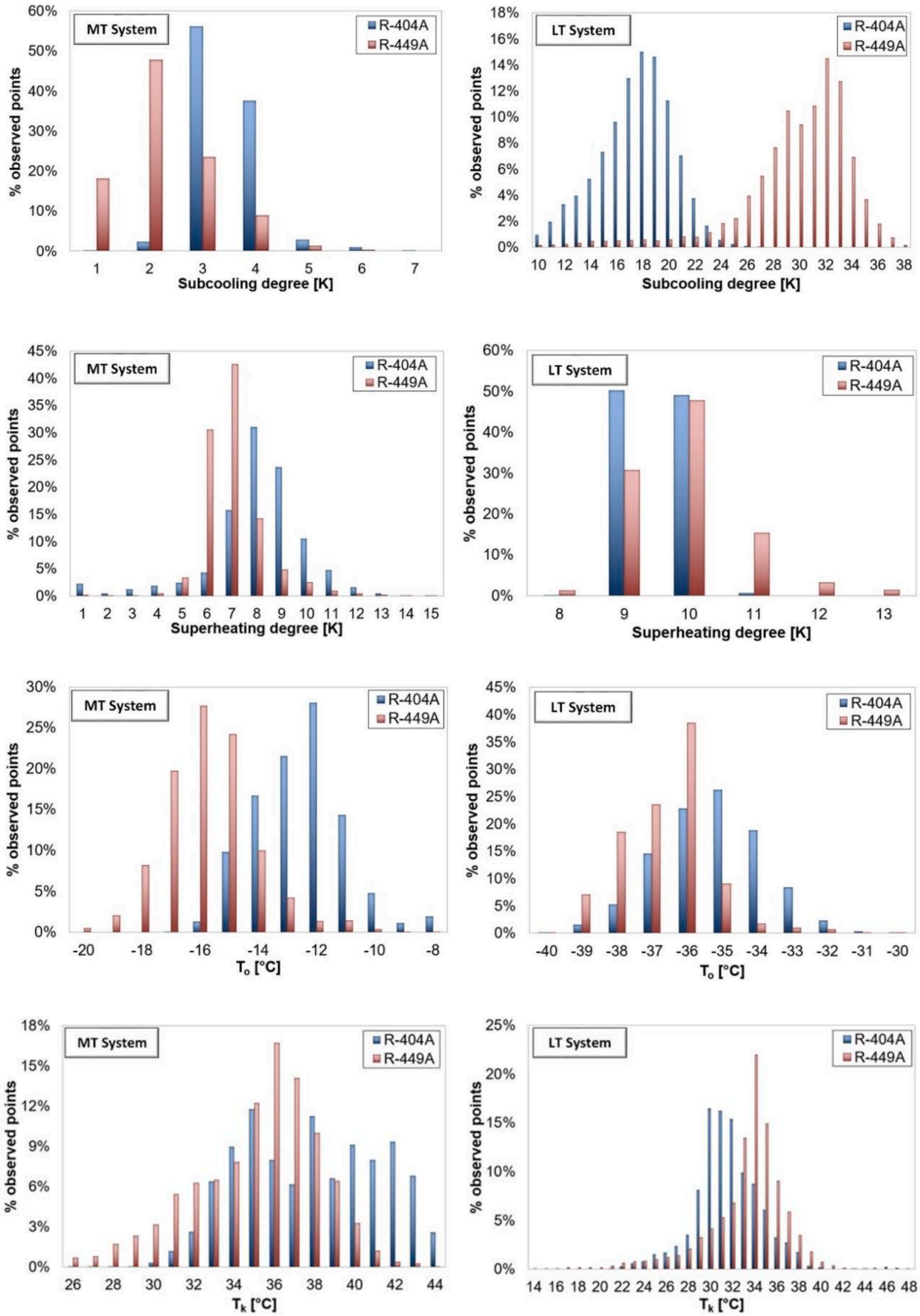

Fig. AI.1. Representative parameters of the supermarket's refrigeration system operation

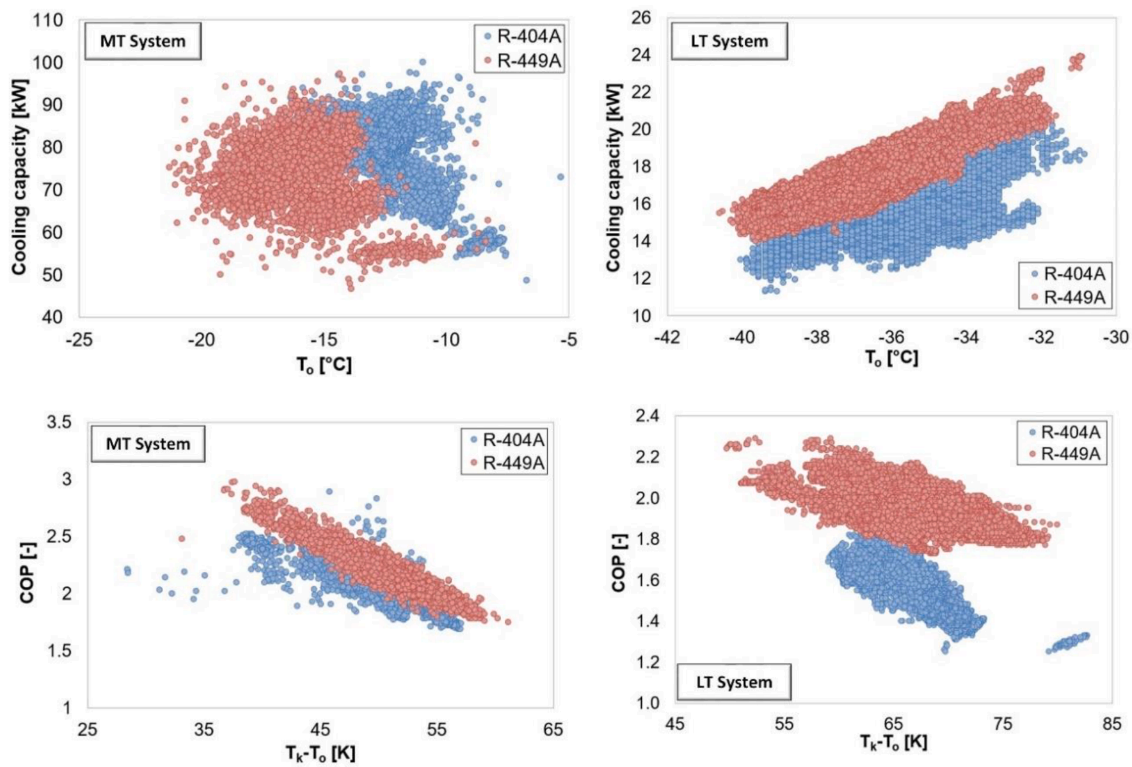

Fig. AI.1. (*continued*).

Annex II. Methodology

As indicated in the text, a flow diagram (Fig. AII.1) is provided to clarify the methodology followed in this paper. It can be used by other researchers and engineers interested in determining the impact of modifying an existing installation without altering its configuration.

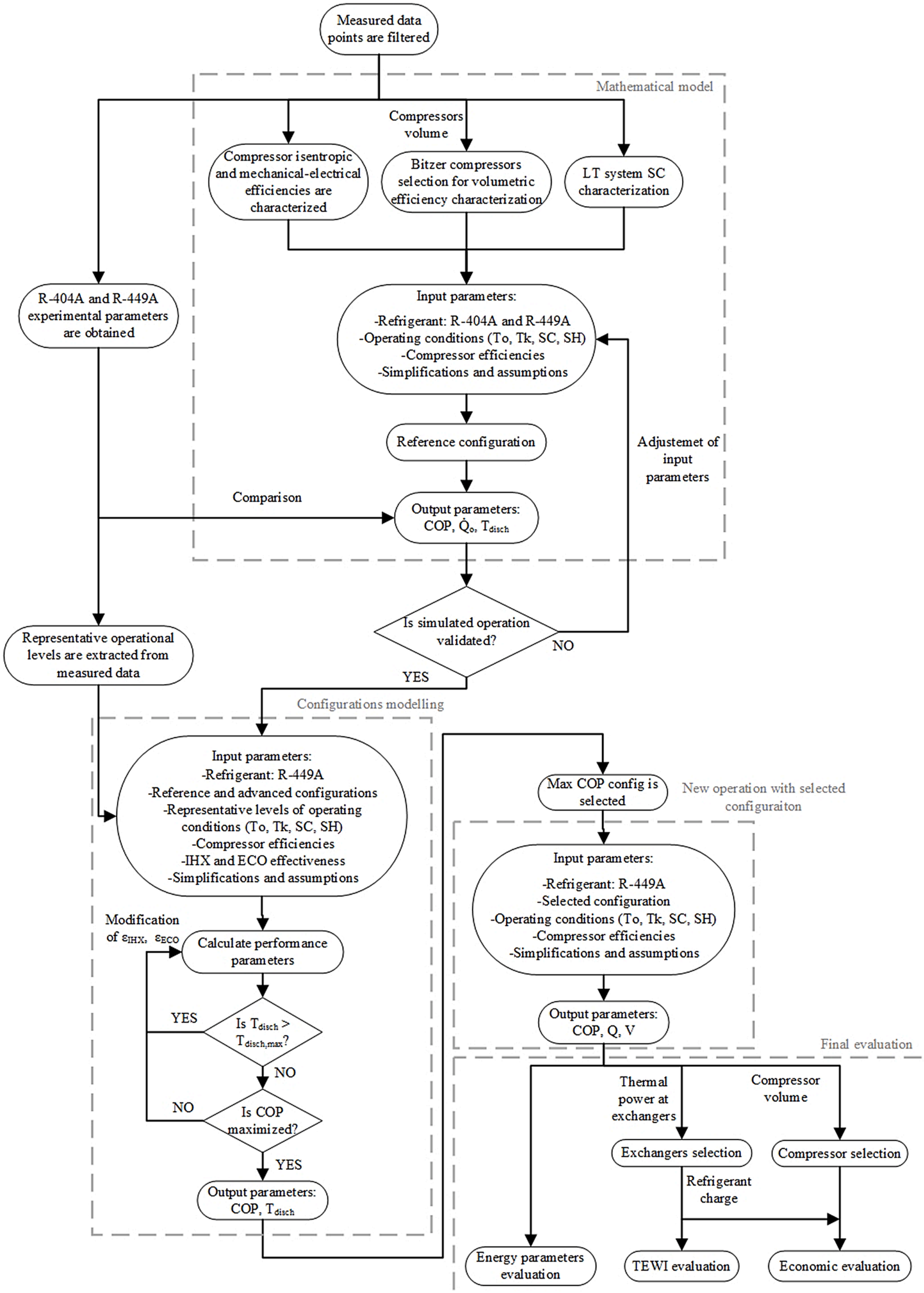

Fig. AII.1. Methodology flow diagram

References

BITZER Kühlmaschinenbau GmbH, 2020. Bitzer Software.

Calm, J.M., 2008. The next generation of refrigerants – Historical review, considerations, and outlook. International Journal of Refrigeration 31, 1123–1133. https://doi.org/10.1016/J.IJREFRIG.2008.01.013.

Citarella, B., Viscito, L., Mochizuki, K., Mauro, A.W., 2022. Multi-criteria (thermo-economic) optimization and environmental analysis of a food refrigeration system working with low environmental impact refrigerants. Energy Conversion and Management, 115152. https://doi.org/10.1016/j.enconman.2021.115152, 253https://doi.org/https://doi.org/.

Deng, Q., Zhang, Z., Hu, X., 2021. Thermoeconomic and environmental analysis of an inverter cold storage unit charged R448A. Sustainable Energy Technologies and Assessments, 101159. https://doi.org/10.1016/j.seta.2021.101159, 45https://doi.org/https://doi.org/.

Domanski, P.A., Brignoli, R., Brown, J.S., Kazakov, A.F., McLinden, M.O., 2017. Low-GWP refrigerants for medium and high-pressure applications. International Journal of Refrigeration 84, 198–209. https://doi.org/10.1016/j.ijrefrig.2017.08.019.

EEA, 2022. Greenhouse gas emission intensity of electricity generation in Europe. European Environmental Agency. https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1. (Accessed 25 February 2022).

Environmental Protection Agency, 2021. Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the American Innovation and Manufacturing Act. Washington (USA).

Eurostat, 2021. Database - Energy [WWW Document]. URL. https://ec.europa.eu/eurostat/web/energy/data/database. accessed 7.19.21.

Gao, E., Cui, Q., Jing, H., Zhang, Z., Zhang, X., 2021. A review of application status and replacement progress of refrigerants in the Chinese cold chain industry. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2021.03.025 https://doi.org/https://doi.org/.

Heredia-Aricapa, Y., Belman-Flores, J.M.M., Mota-Babiloni, A., Serrano-Arellano, J., García-Pabón, J.J.J., 2020. Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410A. International Journal of Refrigeration 111, 113–123. https://doi.org/10.1016/j.ijrefrig.2019.11.012 https://doi.org/https://doi.org/.

IIFIIR, 2020. Review of F-gas regulation - IIR contribution [WWW Document]. URL. https://iifiir.org/en/news/review-of-f-gas-regulation-iir-contribution?utm_source=Newsflash+Opsone+EN&utm_campaign=7e33ebc591. NEWSFLASH_2020_09_24_Fgas_regulation_EN&utm_medium=email&utm_term=0_48d1843cb3-7e33ebc591-211838543 (accessed 12.22.20.

IIR LCCP Working Group, 2016. Guideline for Life Cycle Climate Performance.

Jacob, T.A., Fronk, B.M., 2021. A heat transfer model to predict superheated and saturated condensation of HFC/HFO refrigerant mixtures. International Journal of Heat and Mass Transfer 170, 120947. https://doi.org/10.1016/j.ijheatmasstransfer.2021.120947 https://doi.org/https://doi.org/.

Jacob, T.A., Matty, E.P., Fronk, B.M., 2020. Comparison of R404A condensation heat transfer and pressure drop with low global warming potential replacement candidates R448A and R452A. International Journal of Refrigeration 116, 9–22. https://doi.org/10.1016/j.ijrefrig.2020.03.014.

Kedzierski, M.A., Kang, D., 2016. Horizontal convective boiling of R448A, R449A, and R452B within a micro-fin tube. Science and Technology for the Built Environment. https://doi.org/10.1080/23744731.2016.1186460.

Kim, C.-H., Kim, N.-H., 2021a. Condensation heat transfer and pressure drop of low GWP R-404A-alternative refrigerants (R-448A, R-449A, R-455A, R-454C) in a 7.0-mm outer-diameter horizontal microfin tube. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2021.01.025 https://doi.org/https://doi.org/.

Kim, C.-H., Kim, N.-H., 2021b. Evaporation heat transfer of the low GWP alternative refrigerants (R-448A, R-449A, R-455A, R-454C) for R-404A in a microfin tube. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2021.03.015 https://doi.org/https://doi.org/.

Lee, B.-M., Gook, H.-H., Lee, S.-B., Lee, Y.-W., Park, D.-H., Kim, N.-H., 2021. Condensation heat transfer and pressure drop of low GWP R-404A alternative refrigerants (R-448A, R-449A, R-455A, R-454C) in a 5.6 mm inner diameter horizontal smooth tube. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2020.12.025 https://doi.org/https://doi.org/.

Lillo, G., Mastrullo, R., Mauro, A.W., Pelella, F., Viscito, L., 2019. Experimental thermal and hydraulic characterization of R448A and comparison with R404A during flow boiling. Applied Thermal Engineering 161, 114146. https://doi.org/10.1016/j.applthermaleng.2019.114146 https://doi.org/https://doi.org/.

Makhnatch, P., Mota-Babiloni, A., Khodabandeh, R., Haro-Ortuño, J., 2018. Field measurements of a R404A low-temperature supermarket refrigeration system retrofitted with R449A. In: 5th IIR Conference on Sustainability and the Cold Chain. Chinese Association of Refrigeration (CAR), Beijing (China), pp. 468–474. https://doi.org/10.18462/iir.iccc.2018.0061.

Makhnatch, P., Mota-Babiloni, A., Rogstam, J., Khodabandeh, R., 2017. Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system. International Journal of Refrigeration 76, 184–192. https://doi.org/10.1016/J.IJREFRIG.2017.02.009.

Mateu-Royo, C., Arpagaus, C., Mota-Babiloni, A., Navarro-Esbrí, J., Bertsch, S.S., 2021. Advanced high temperature heat pump configurations using low GWP refrigerants for industrial waste heat recovery: A comprehensive study. Energy Conversion and Management, 113752. https://doi.org/10.1016/j.enconman.2020.113752, 229https://doi.org/https://doi.org/.

McLinden, M.O., Brown, J.S., Brignoli, R., Kazakov, A.F., Domanski, P.A., 2017. Limited options for low-global-warming-potential refrigerants. Nature Communications 8, 1–9. https://doi.org/10.1038/ncomms14476, 20171 8.

Mendoza-Miranda, J.M., Mota-Babiloni, A., Navarro-Esbrí, J., 2016. Evaluation of R448A and R450A as low-GWP alternatives for R404A and R134a using a micro-fin tube evaporator model. Applied Thermal Engineering 98. https://doi.org/10.1016/j.applthermaleng.2015.12.064.

Morrow, J.A., Huber, R.A., Nawaz, K., Derby, M.M., 2021. Flow condensation heat transfer performance of natural and emerging synthetic refrigerants. International Journal of Refrigeration 132, 293–321. https://doi.org/10.1016/j.ijrefrig.2021.09.014 https://doi.org/https://doi.org/.

Mota-Babiloni, A., Barbosa, J.R., Makhnatch, P., Lozano, J.A., 2020. Assessment of the utilization of equivalent warming impact metrics in refrigeration, air conditioning and heat pump systems. Renewable and Sustainable Energy Reviews 129, 109929. https://doi.org/10.1016/j.rser.2020.109929 https://doi.org/https://doi.org/.

Mota-Babiloni, A., Haro-Ortuño, J., Navarro-Esbrí, J., Barragán-Cervera, Á., 2018. Experimental drop-in replacement of R404A for warm countries using the low GWP mixtures R454C and R455A. International Journal of Refrigeration 91, 136–145. https://doi.org/10.1016/j.ijrefrig.2018.05.018.

Mota-Babiloni, A., Makhnatch, P., 2021. Predictions of European refrigerants place on the market following F-gas regulation restrictions. International Journal of Refrigeration 127, 101–110. https://doi.org/10.1016/j.ijrefrig.2021.03.005 https://doi.org/https://doi.org/.

Mota-Babiloni, A., Navarro-Esbrí, J., Barragán, Á., Molés, F., Peris, B., 2014. Theoretical comparison of low GWP alternatives for different refrigeration configurations taking R404A as baseline. International Journal of Refrigeration 44. https://doi.org/10.1016/j.ijrefrig.2014.04.015.

Mota-Babiloni, A., Navarro-Esbrí, J., Peris, B., Molés, F., Verdú, G., 2015. Experimental evaluation of R448A as R404A lower-GWP alternative in refrigeration systems. Energy Conversion and Management 105. https://doi.org/10.1016/j.enconman.2015.08.034.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D, Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M.(Eds.) (Eds.), Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, CambridgeUnited KingdomNew YorkN.YUSA. https://doi.org/10.1017/CBO9781107415324.018.

Oruç, V., Devecioğlu, A.G., 2021. Experimental investigation on the low-GWP HFC/HFO blends R454A and R454C in a R404A refrigeration system. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2021.04.007 https://doi.org/https://doi.org/.

Oruç, V., Devecioğlu, A.G., 2020. Experimental assessment of the retrofit of an internal heat exchanger in refrigeration systems: The effect on energy performance and system operation. Applied Thermal Engineering 180, 115843. https://doi.org/10.1016/j.applthermaleng.2020.115843 https://doi.org/https://doi.org/.

Rogstam, J., Bolteau, S., Makhnatch, P., Khodabandeh, R., 2016. Evaluation of a potential R404A replacement - Field test with R449A. Stockholm (Sweden).

Klein, S.A., 2019. Engineering Equation Solver.

Sawalha, S., Piscopiello, S., Karampour, M., Manickam, L., Rogstam, J., 2017. Field measurements of supermarket refrigeration systems. Part II: Analysis of HFC refrigeration systems and comparison to CO2 trans-critical. Applied Thermal Engineering 111, 170–182. https://doi.org/10.1016/J.APPLTHERMALENG.2016.09.073.

Sharma, V., Fricke, B., Bansal, P., 2014. Comparative analysis of various CO2 configurations in supermarket refrigeration systems. International Journal of Refrigeration 46, 86–99. https://doi.org/10.1016/J.IJREFRIG.2014.07.001.

United Nations Environment Programme (UNEP), 2016. Twenty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. Decision XXVIII/— Further Amendment of the Montreal Protocol.

Yang, Zhao, Feng, B., Ma, H., Zhang, L., Duan, C., Liu, B., Zhang, Y., Chen, S., Yang, Zongyu, 2021. Analysis of Lower GWP and Flammable Alternative Refrigerants. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2021.01.022 https://doi.org/https://doi.org/.

Further reading

Alam, Md.S., Jeong, J.H., 2020. Calculation of the thermodynamic properties of R448A and R449A in a saturation temperature range of 233.15 K to 343.15 K using molecular dynamics simulations. International Communications in Heat and Mass Transfer 116, 104717. https://doi.org/10.1016/j.icheatmasstransfer.2020.104717 https://doi.org/https://doi.org/.

Makhnatch, P., Mota-Babiloni, A., Rogstam, J., Khodabandeh, R., 2017b. Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system. International Journal of Refrigeration 76, 184–192. https://doi.org/10.1016/J.IJREFRIG.2017.02.009.

Properties of lubricants for refrigeration system with the low GWP refrigerants. In: Nakajima, S., Matsumoto, T., Kawaguchi, Y. (Eds.), 2018. International Refrigeration and Air Conditioning Conference Paper 1972.

Saito, R., Sundaresan, S.G., 2017. Refrigeration oils for low GWP refrigerants in various applications. IOP Conference Series: Materials Science and Engineering 232, 12093. https://doi.org/10.1088/1757-899x/232/1/012093.