REFRIGERATION SCIENCE AND TECHNOLOGY PROCEEDINGS

CHINESE ASSOCIATION OF REFRIGERATION (CAR) FOR COOPERATION
WITH THE INTERNATIONAL INSTITUTE OF REFRIGERATION (IIR)

3rd IIR Conference on HFO Refrigerants and Low GWP Blends

Shanghai, China
April 5 – 7, 2023

INSTITUT INTERNATIONAL DU FROID
INTERNATIONAL INSTITUTE OF REFRIGERATION

ISBN: 978-2-36215-052-4
ISSN: 0151-1637
Code: 2023/1

PROCEEDINGS

REFRIGERATION SCIENCE AND TECHNOLOGY

3rd IIR Conference on HFO Refrigerants and Low GWP Blends

April 5-7, 2023

Grand Mercure Shanghai Century Park, Shanghai, China

Published by

Chinese Association of Refrigeration (CAR)

NO.67 FUCHENG ROAD, HAIDIAN DISTRICT,
BEIJING, CHINA
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http://hfo2023.car.org.cn

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PAPERID: 0002
DOI: 10.18462/iir.HFO2023.0002

INFLUENCE OF SUBCOOLING IN R449A SUPERMARKET LOW-TEMPERATURE REFRIGERATION CIRCUIT USING MEDIUM TEMPERATURE COOLING LOAD

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ABSTRACT

This work studies the impact of subcooling in supermarket refrigeration systems with medium and low-temperature requirementsbased on a vapor compression single-stage with a subcooler. The energy performance (measured by the coefficient of performance, COP) of the low-temperature circuit has been analyzed considering the current system (with subcooling) and compared with a semi-empirical scenario without a subcooler. For a fixed cooling capacity, the new design compressors selected for R-449A reduce the compressor power consumption compared to the measurements, increasing COP, particularly at low-temperature lifts. Among the subcooler and no subcooler options, the differences are negligible in overall COP because the differences in COP for each stage are compensated. Carbon emissions calculated with the total equivalent warming impact (TEWI) are slightly lower in the configuration without a subcooler. From an energy and environmental point of view, it is not advisable to use subcooling in R-449A supermarket refrigeration.

Keywords: HFO mixtures, Commercial Refrigeration, Global Warming Potential (GWP), COP, Subcooler, R404A replacement

1.INTRODUCTION

Cold chain is essential for food conservation and freezing while keeping the maximum standards and avoiding the growth of bacteria. However, 12% of food in 2017 (526 Mt) was lost due to an insufficient cold chain or refrigeration (Sarr et al., 2021).In the current coldchain, most carbon emissions (60%) originate from refrigeration equipment's electricity consumption (261 MtCO_2e). An improved cold chain with significantly lower food losses would increase these emissions to 589MtCO_2e. Therefore, highly energy-efficient equipment is required for commercial refrigeration.

Mota-Babiloni et al. (2022) proposed advanced configurations in a supermarket refrigeration unit operating with R-404A and retrofitted to R-449A. Parallel compression is the configuration that results in higher COP, but a simple retrofit to lower GWP refrigerants was the most convenient option. Citarella et al. (2022) demonstrated that R449A refrigerantsperform better for mid-term commercial refrigeration in the European market. The optimal configuration in terms of energy performance has not the lowest environmental impact.Llopis et al. (2020) proposed a novel TEWI methodology considering the dependence of energy consumption with charge evolution and studied the impact on commercial refrigeration.

Cui et al. (2020)analyzed CO_2 booster configurations and three reference systems fromenergy, economic and environmental perspectives. Considering the results, CO_2 booster configurations are recommended for northern China. Still, the most advanced solution in Europe is unsuitable for China's hot climate cities, where R134a/CO_2 cascade refrigeration system can be considered a short-term solution.Giunta and Sawalha (2021) demonstrated that a supermarket based on CO_2 refrigeration could save up to 18% of the annual CO_2e emissions of the supermarket and increase benefits to 16% of the annual energy cost by selling part of the heat recovered to the district heating network operator.Karampour and Sawalha (2018) concluded that two-stage heat recovery, parallel compression, AC integration, and flooded evaporation are important improvements for CO_2refrigeration systems. Mechanical sub-cooling and gas cooler evaporative cooling are technologies considered arbitrary because of their impact and limitations.

Regarding mechanical subcooling,(Llopis et al., 2018)found benefits for CO_2transcritical refrigeration. Regarding external subcooling methods, they highlighted dedicated mechanical subcooling.In this configuration, an auxiliary vapour compression system subcools the refrigerant at the condenser outlet before entering the expansion valve. The auxiliary system operates with a reduced temperature lift between the cold source and hot sink, reaching high COP values. Among other works, (Nebot-Andrés et al., 2022) compared this technology with other proposals for transcriticalCO_2 refrigeration.Experimental tests validated the energy increase of the mechanical subcooling cycle compared to parallel compression.(ERDINC, 2022) proposed an expander-compressor booster-enhanced subcooling vapor compression cycle and compared R134a, R1234yf, R32, R290, R1270, and R600a.

(She et al., 2018) reviewed several works considering mechanical subcooling that concluded with COP benefits. (Qureshi and Zubair, 2012) investigated refrigerant combinations in dedicated mechanical subcooling vapor compression cycles. R134a caused the best results concerning COP, COP gain and relative compressor sizing in basic cycle and when dedicated mechanical subcooling is considered. In retrofit cases, dedicated mechanical subcooling is more suited to R134a as the main cycle becauseit has a negligible influence on the performance parameters when changing to the subcooler cycle. Besides, a subcooler between the medium-temperature (MT) refrigeration system and the low-temperature (LT) refrigeration system can be used for energy saving (Yang and Zhang, 2011).Optimal subcooler size and subcooling control increaseenergy savings of a two-temperature supermarket refrigeration system to 27% or 20% using R404A or R134a, respectively.

(Qureshi and Zubair, 2013) indicated the need for experimental work on residential, commercial, and industrial refrigeration equipment needs to the integrated subcooling cycle. This paper proposes a semi-empirical investigation of integrating subcooling units in an indirect supermarket refrigeration unit operating with R449A.

2.METHODS

2.1 Baseline

The supermarket refrigeration system is described in (Makhnatch et al., 2017), medium-temperature refrigeration units, and (Makhnatch et al., 2018), low-temperature refrigeration units. These works study both systems separately, analyzing the operational and energy performance when using R404A and R449A as a drop-in (or light retrofit) replacement. Figure 1 shows the schematic diagram and thermal and hydraulic connections between these circuits. All information necessary for describing the systems is included in the abovementioned papers.

The operation of the supermarket refrigeration unit (temperatures, pressures, compressor power consumption) was measured for an extended period using both refrigerants. Previous papers published have analyzed the energy and operational performance of the unit. The main conclusion was that R449A retrofit is beneficial in terms of operation, energy and environment. According to this, Mota-Babiloni et al. (2022)previous work confirms the economic advantage of the R449A light retrofit compared to the R404A baseline.As R449A supermarket refrigeration benefits have already been confirmed, this cycle is taken as the reference, SM, in the rest of the work. The steady-state operation of this unit will be considered as inputs (evaporation and condensation temperature) for the model developed to determine the semi-empirical operation.

2.2 Simulation strategy

Different scenarios are analyzed in this paper, considering the supermarket operation mentioned in the previous subsection as a baseline, keeping R449A as the refrigerant and selecting new compressors:'SC'configuration for the simulation using MT evaporator to provide LT subcooling (initial cycle design).'no SC'configuration for the simulation without a subcooler. Both cycles operate independently, and no subcooling is provided by a subcooler, liquid-to-suction heat exchanger, or any other means.

No SC configuration removes the LT subcooling provided by the MT units; therefore, new compressors are required to provide lower cooling capacity in the MT cycle and higher cooling capacity in the LT cycle. The same software for compressor selection has been used in the cycle with subcooling 'SC' to result in comparable compressor technology, response, and efficiencies.

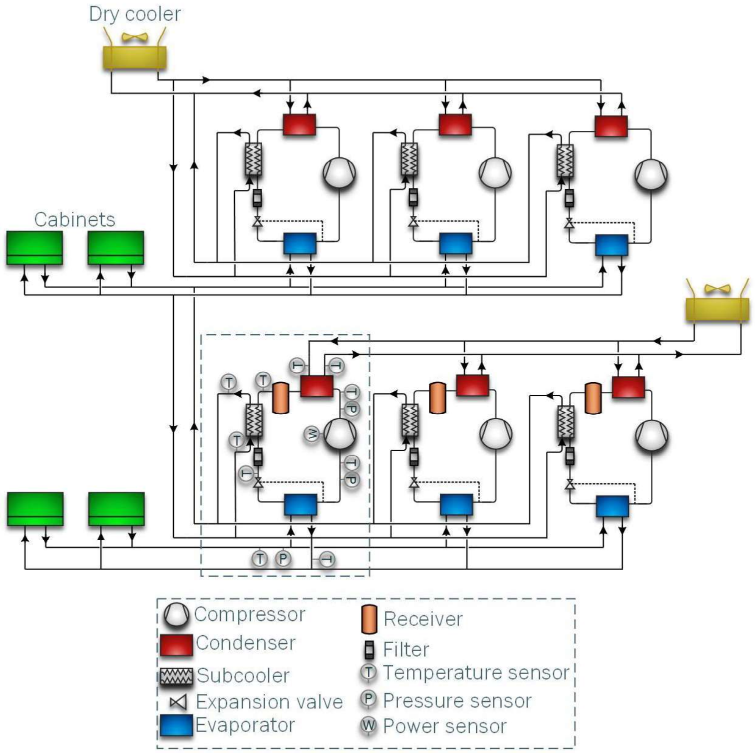

Figure 1: Supermarket refrigeration system schematic diagram

Thermodynamic states of refrigerants have been calculated using REFPROP v10.0. Basic vapor compression cycles have been simulated using MT and LT cooling capacity, evaporation, and condensation temperatures. For the simulation of the compressor efficiencies, subsection 2.3 exposes the methodology followed.

2.3 Compressor selection and simulation

The compressorselection is carried out using the current version ofBITZER software (v6.17.9rev2794). As in the original system, semi-hermetic reciprocating compressors have been chosen. Each circuit's average cooling capacity and operational temperatures (evaporation and condensation) and scenario have been used as input. The resulting compressor models and main details can be seen in Table 1, where it can be extracted that 4 kW is the cooling load transferred in the subcooler. Moreover, when the subcooling is removed, the MT compressor volume displacement is reduced by 18% (6 cylinders instead of 8).

Table 1: Details of compressors included in the simulation

Circuit and scenario	Cooling load	Compressor model	Volume displacement (1450rpm at 50Hz)
MT SC	74 kW	8GE-60Y	185 m^3h^{-1}
LT SC	12.5 kW	4GE-23Y	84.5 m^3h^{-1}
MT no SC	70 kW	6FE-44Y	151.6 m^3h^{-1}
LT no SC	16.5 kW	4FE-28Y	101.8 m^3h^{-1}

In Table 2,equations required for determining the compressors’ volumetric and isentropic efficiency are calculated through regressions depending on the evaporation and condensation temperatures. A high agreement (R^2) is observed between the correlations and the data provided by the compressor selection software. Besides isentropic and volumetric efficiencies, the electromechanical efficiency for the compressor-motor set is considered that of the IE4 motors (0.94 for MT and 0.92 for LT).

Table 2: Volumetric and isentropic compressor efficiency of simulated compressors

System	Equation	R^2
MT SC	$\eta_{vol} = 1.0328 + 0.00527\,T_o - 0.00553\,T_k$	0.99
	$\eta_{is} = 0.4353 - 0.00799\,T_o + 0.0072\,T_k - 0.0000625\,T_o^2 - 0.00006525\,T_k^2 + 0.000$	0.99
LT SC	$\eta_{vol} = 1.1827 + 0.00955\,T_o - 0.00592\,T_k$	0.94
	$\eta_{is} = 0.3398 - 0.01624\,T_o + 0.01044\,T_k - 0.0002587\,T_o^2 - 0.0001282\,T_k^2 + 0.000$	0.92
MT no SC	$\eta_{vol} = 1.0339 + 0.00473\,T_o - 0.00438\,T_k$	0.99
	$\eta_{is} = 0.4363 - 0.009371\,T_o + 0.008621\,T_k - 0.0001226\,T_o^2 - 0.00008358\,T_k^2 + 0.$	0.99
LT no SC	$\eta_{vol} = 1.1658 + 0.00902\,T_o - 0.00591\,T_k$	0.92
	$\eta_{is} = 0.3281 - 0.01613\,T_o + 0.01143\,T_k - 0.000243\,T_o^2 - 0.0001292\,T_k^2 + 0.0001$	0.91

2.4 Equations

The coefficient of performance of each cycle is calculated as indicated in Eq. (1). For the overall COP, the cooling capacity delivered to the refrigerated and frozen cabinets are summed, and divided by the sum of compressor power consumption.

$$COP = \frac{\dot{Q}_{evap}}{\dot{P}_{el}} \qquad \text{Eq. (1)}$$

$$COP_{overall} = \frac{\sum \dot{Q}_{evap}}{\sum \dot{P}_{el}} \qquad \text{Eq. (2)}$$

3. RESULTS

3.1 Energy performance

This section shows the COP measured and simulated in the proposed configurations. Figure 2 shows the COP of individual cycles for MT and LT stages. Given that the simulation uses evaporation and condensation temperatures and cooling capacity as input, COP results in the simulation are less scattered. However, the trend at hightemperature lift is comparable for MT, and at all conditions for LT.

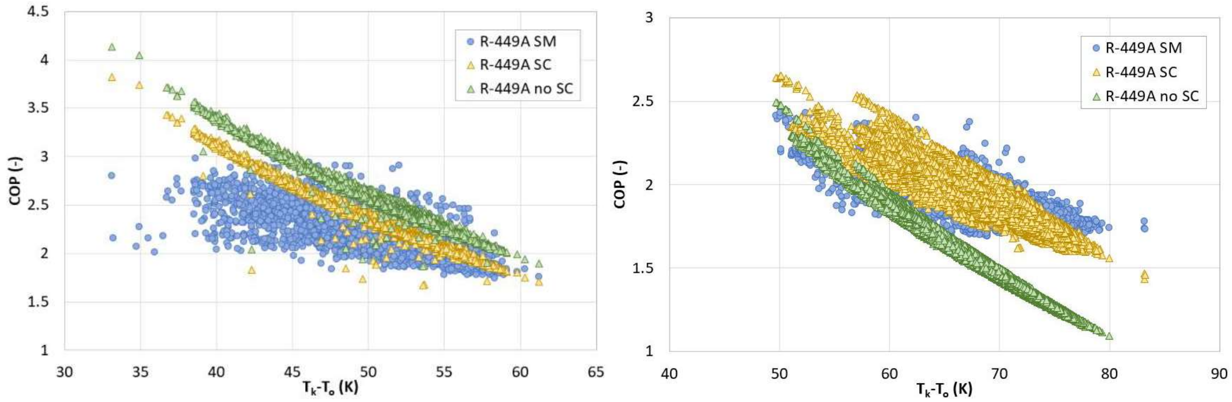

Figure 2: COP of MT (left) and LT (right) circuits

Regarding the MT circuit, the average COP values for SM,SC and no SC are 2.20, 2.30, and 2.53, respectively. The new compressor increases the COP if SC and SM are compared. Then, the no SC situation results in higher COP because all the cooling capacity is used in the same cycle. The model can be considered highly accurate for the LT circuit as SM and SC COP values are comparable, 1.88. For the no SC scenario, the average COP is 1.47. This reduction is because of the removal of subcooling, so all the cooling capacity must be provided by a higher mass flow rate, which increases the compressor power consumption and decreases COP.

For the energy performance simulation, the cooling capacity is fixed, so the difference in COP is caused by compressor power consumption. Figure 3 shows the resulting compressor power consumption. In the MT circuit, as the SC configuration requires a higher cooling capacity to provide refrigeration to frozen cabinets and LT subcooler, the mass flow rate is higher and increases the compressor power consumption. The contrary occurs in the LT circuit, as explained above. The average compressor power consumption values for the MT circuit are 34.1, 33.2 and 27.9 kW for SM, SC, and no SC configurations, respectively. Then, concerning the LT circuit, the average compressor power consumption values are 8.8, 8.9 and 10.6 kW for SM, SC, and no SC configurations, respectively.

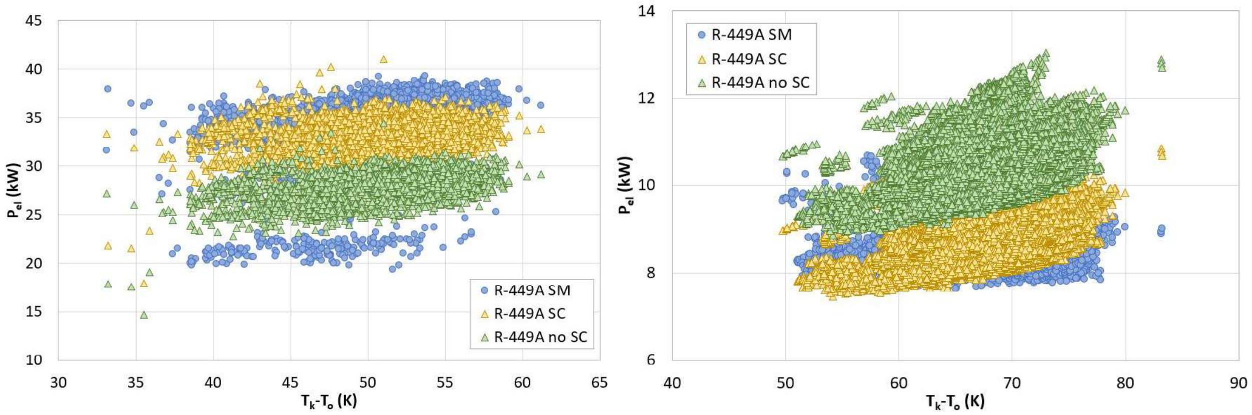

Figure 3: Compressor power consumption of MT (left) and LT (right) circuits

The overall COP is calculatedto determine the energy benefit of the supermarket refrigeration system, Figure 4. The axes represent the temperature lifts for each circuit. At high temperature lifts, the three configurations show a comparable overall COP value. Contrarily, for low temperature lifts, the SM configuration performs below simulations using new design compressors. Comparing SC and no SC configurations, the overall COP is comparable for most conditions, being slightly higher for the no SC configuration at low temperature lifts.

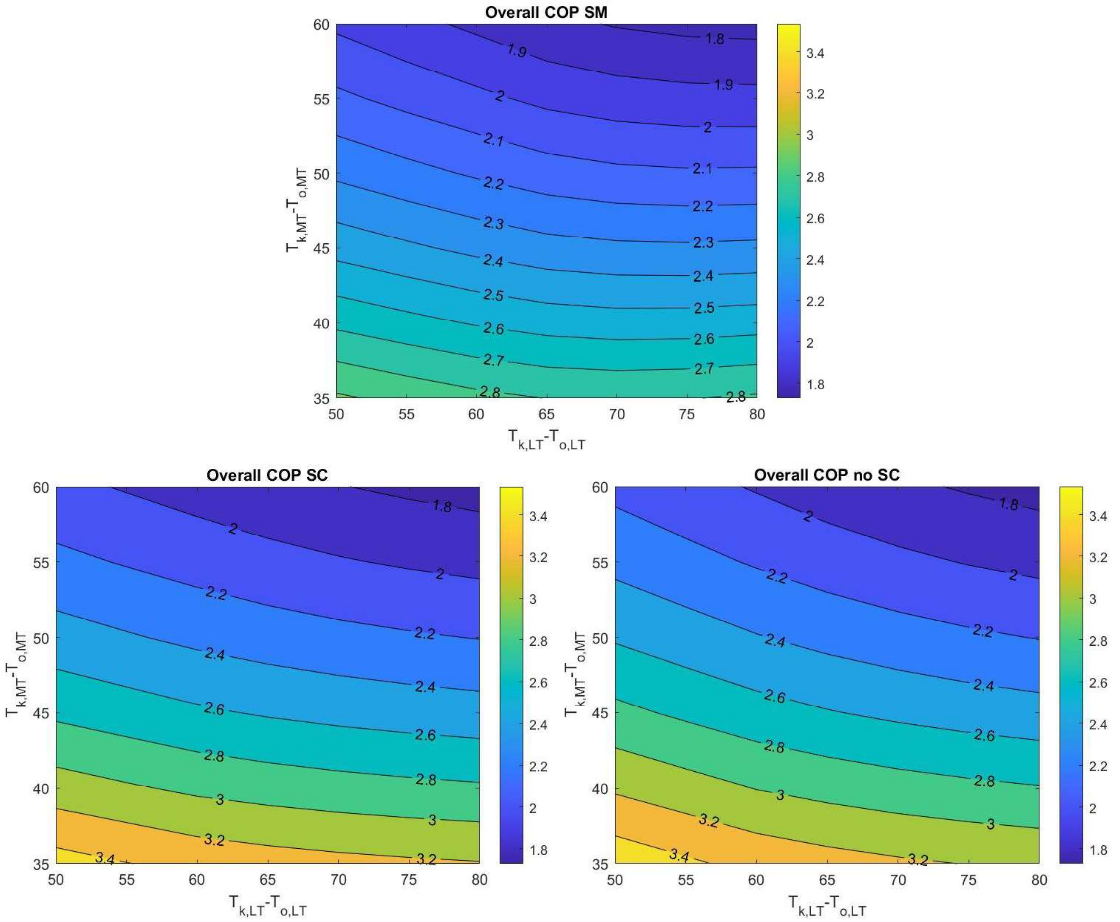

Figure 4: Overall COP for SM (top), SC (down left) and no SC (down right) circuits

3.2 Carbon footprint assessment

The total equivalent warming impact (TEWI) is used as the indicator for the carbon footprint. Indications provided by (Mota-Babiloni et al., 2020) have been followed.For the TEWI, the refrigerantcharge in the subcooler is calculated with the SWEP design software because it is removed for the no SC configuration. The measured and simulated compressor power consumption has been extended over a year.TEWI has been calculated for the whole unit, considering the 3 circuits for MT and another 3 for LT. As the baseline supermarket was located in Sweden, the Swedish carbon emission factor is taken, 0.0088 kgCO$_2$e kWh^{-1}.Figure 5 shows the TEWI results indicating the type of carbon emissions. A new design compressor can reduce carbon emissions over the SM solution. Then, as the no SC configuration requires less refrigerant charge and the COP was slightly higher, both direct and indirect emissions are reduced.

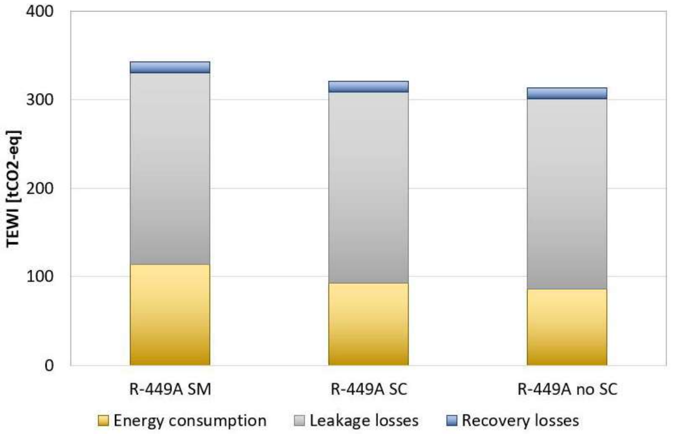

Figure 5: TEWI

4.CONCLUSIONS

Subcooling can translate cooling capacity from an MT circuit to an LT. This is a common practice because supermarket refrigeration systems usually present a higher cooling capacity in the MT circuit. This paper compares the options with and without a subcooler to determine the benefit based on a semi-empirical analysis. After selecting new compressors adjusted to the required cooling capacity, the energy analysis reveals that COP is comparable between both options and that the carbon footprint is lower without a subcooler.

ACKNOWLEDGEMENTS

Adrián Mota-Babiloni acknowledges contract IJC2019-038997-I, funded by MCIN/AEI/10.13039/501100011033. Pau Giménez-Prades acknowledges grant CIACIF/2021/182, funded by the GeneralitatValenciana (GV) and the European Social Fund (ESF).Cosmin Mihai Udroiu acknowledges grant PRE2021-097369 funded by MCIN/AEI/10.13039/501100011033 and by "ESF Investing in your future".

NOMENCLATURE

$\dot{P}_{el}$	Power consumption (kW)	*vol*	volumetric
T	temperature (°C)	*is*	isentropic
k	condensation	*o*	evaporation
COP	Coefficient of performance (-)	$\dot{Q}_{evap}$	Cooling capacity (kW)

REFERENCES

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 Convers Manag 253, 115152. https://doi.org/https://doi.org/10.1016/j.enconman.2021.115152

Cui, Q., Gao, E., Zhang, Z., Zhang, X., 2020. Preliminary study on the feasibility assessment of CO2 booster refrigeration systems for supermarket application in China: An energetic, economic, and environmental analysis. Energy Convers Manag 225, 113422. https://doi.org/https://doi.org/10.1016/j.enconman.2020.113422

ERDINC, M.T., 2022. Performance simulation of expander-compressor boosted subcooling refrigeration system. International Journal of Refrigeration. https://doi.org/https://doi.org/10.1016/j.ijrefrig.2022.12.013

Giunta, F., Sawalha, S., 2021. Techno-economic analysis of heat recovery from supermarket's CO2 refrigeration systems to district heating networks. Appl ThermEng 193, 117000. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2021.117000

Karampour, M., Sawalha, S., 2018. State-of-the-art integrated CO2 refrigeration system for supermarkets: A comparative analysis. International Journal of Refrigeration 86, 239–257. https://doi.org/10.1016/J.IJREFRIG.2017.11.006

Llopis, R., Calleja-Anta, D., Maiorino, A., Nebot-Andrés, L., Sánchez, D., Cabello, R., 2020. TEWI analysis of a stand-alone refrigeration system using low-GWP fluids with leakage ratio consideration . International Journal of Refrigeration 118, 279–289. https://doi.org/10.1016/j.ijrefrig.2020.05.028

Llopis, R., Nebot-Andrés, L., Sánchez, D., Catalán-Gil, J., Cabello, R., 2018. Subcooling methods for CO2 refrigeration cycles: A review. International Journal of Refrigeration 93, 85–107. https://doi.org/https://doi.org/10.1016/j.ijrefrig.2018.06.010

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

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/https://doi.org/10.1016/j.rser.2020.109929

Mota-Babiloni, A., Giménez-Prades, P., Makhnatch, P., Rogstam, J., Fernández-Moreno, A., Navarro-Esbrí, J., 2022. Semi-empirical analysis of HFC supermarket refrigeration retrofit with advanced configurations from energy, environmental, and economic perspectives. International Journal of Refrigeration. https://doi.org/https://doi.org/10.1016/j.ijrefrig.2022.02.017

Nebot-Andrés, L., Calleja-Anta, D., Sánchez, D., Cabello, R., Llopis, R., 2022. Experimental assessment of dedicated and integrated mechanical subcooling systems vs parallel compression in transcritical CO2 refrigeration plants. Energy Convers Manag 252, 115051. https://doi.org/https://doi.org/10.1016/j.enconman.2021.115051

Qureshi, B.A., Zubair, S.M., 2013. Mechanical sub-cooling vapor compression systems: Current status and future directions. International Journal of Refrigeration 36, 2097–2110. https://doi.org/https://doi.org/10.1016/j.ijrefrig.2013.07.026

Qureshi, B.A., Zubair, S.M., 2012. The effect of refrigerant combinations on performance of a vapor compression refrigeration system with dedicated mechanical sub-cooling. International Journal of Refrigeration 35, 47–57. https://doi.org/https://doi.org/10.1016/j.ijrefrig.2011.09.009

Sarr, J., Dupont, J., Guilpart J, 2021. The carbon footprint of the cold chain, 7th Informatory Note on Refrigeration and Food. Paris. https://doi.org/http://dx.doi.org/10.18462/iir.INfood07.04.2021

She, X., Cong, L., Nie, B., Leng, G., Peng, H., Chen, Y., Zhang, X., Wen, T., Yang, H., Luo, Y., 2018. Energy-efficient and -economic technologies for air conditioning with vapor compression refrigeration: A comprehensive review. Appl Energy 232, 157–186. https://doi.org/10.1016/J.APENERGY.2018.09.067

Yang, L., Zhang, C.-L., 2011. On subcooler design for integrated two-temperature supermarket refrigeration system. Energy Build 43, 224–231. https://doi.org/https://doi.org/10.1016/j.enbuild.2010.09.016