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Experimental evaluation of different refrigeration system configurations using CO2-based blends as refrigerants

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ABSTRACT

Recently, blends created by mixing CO_2 with another fluid with a higher critical temperature are being considered, to allow subcritical operation at high outdoor temperature, thus increasing the COP. The goal of this work is to evaluate through an experimental approach the energy performance of the mixture CO_2/R152a. Two compositions, (95/5% and 90/10%) were tested in a single-stage refrigeration plant with and without an internal heat exchanger, and their performance is compared to that with pure CO_2. Several secondary fluid inlet temperature values at the gas cooler/condenser are considered (20-25-30-35-40°C), while the inlet temperature of the secondary fluid at the evaporator is maintained at 2.5°C. Using the investigated mixtures an enhancement of the COP compared to pure CO_2 is observed, when the base cycle is implemented, for temperatures above 25ºC, reaching the largest increment at highest secondary fluid inlet temperature. Instead, when using the IHX, no improvement in the COP is obtained.

Keywords: Refrigeration, Carbon Dioxide, Mixture, COP, Internal heat exchanger, R152a

1. INTRODUCTION

The 2nd F-Gas Regulation (European Commission, 2014) supposed the start of phasing-out high-GWP refrigerants in medium and large refrigeration systems, especially in supermarket centralized refrigeration. From 2014 on, CO_2-based refrigeration supermarkets proliferated in Europe, reaching more than 57000 units in 2022 according to ATMOsphere (2022). Among them, 87.7% CO_2-stores implement medium or large-sized architectures (cooling capacity >40kW), 3.5% are industrial systems and only 8.8% are systems for low-sized capacities, which are usually known as condensing units. The higher greater diffusion of large plants is explained with economic reasons, since they allow high investment rate, so they can rely on advanced refrigeration architectures such as parallel compression (Karampour and Sawalha, 2018; Nebot-Andrés et al., 2021a), ejectors (Gullo et al., 2018; Purohit et al., 2018), mechanical subcooling systems (Catalán-Gil et al., 2019; Bush et al., 2017; Nebot-Andrés et al., 2022, D'Agaro et al., 2021), flooded evaporator (Lata and Gupta, 2020; Söylemez et al., 2022), among others. However, the investment in high-efficient CO_2 cycles for low-capacity systems is not usually cost-efficient, so they usually still rely on condensing units operating with HFC or HFO fluids.

During the last years, there has been a rising interest to extend the use of CO_2 to small systems. One of the ways that could make the CO_2 efficient also in small refrigerating plants is the use of CO_2-based mixtures. From a theoretical perspective, Kumar and Kumar (2019) investigated the use of the mixture CO_2/R-290 (85/15%). They reported that the use of the mixture instead of the pure CO_2 was able to reduce the optimum high pressure allowing subcritical operation, but they did not evaluate COP differences. Zhao et al. (2022)

considered CO_2 blending with butane, isobutane and two HFOs for the application in single and two-stage cycles with IHX for LT applications. All combinations offered COP increments in relation to pure CO_2. Xie et al. (2022) extended the analysis considering R-152a and R-161 for single-stage cycles. At the evaluated conditions, they predicted 26% increase of COP in relation to CO_2. Vaccaro et al. (2022) enlarged the analysis with three HCs (R-600a, R-600 and R-290) and three HFOs (R-1234ze(E), R-1234ze(Z) and R-1233zd(E)). They concluded that at an evaporation temperature of -15ºC and a temperature of 40ºC at the exit of the gas-cooler, the blends CO_2/R1234yf and CO_2/R-290 were the most efficient, offering COP increments up to 12.8% and 7.9% respectively, using a single-stage configuration with IHX. And recently, Martínez-Angeles et al. (under revision) evaluated CO_2-doping with R-152a, R-1234yf, R-1234ze(E) and R-1233zd(E) considering the single-stage cycle with IHX and the parallel compression. They predicted maximum increments up to 5.8% for the IHX layout and 10.0% for the parallel compressor cycle.

Experimental validation of the theoretical hypothesis is scarce, but Tobaly et al. (2018) were able to measure 19.7% COP increment in relation to CO_2 using the mixture CO2/R-290 (90/10%) at air-conditioning conditions with a single-stage test rig with IHX and scroll compressor. Later, Yu et al. (2018) extended the analysis of CO_2/R-290 mixtures in air conditioning systems measuring 22% COP increments. And finally, Sánchez et al. (2019) (2020) evaluated R-290, R-1270 and R-32 as doping agents of CO_2 in a beverage cooler for positive temperature applications. In this case, under fixed climatic chamber conditions, they measured energy consumption reductions in relation to pure CO_2 up to 17.2% at an environment temperature of 25ºC and up to 12.2% at 30ºC. These works confirm that it is possible to enhance the performance of basic CO_2 cycles by doping it with a small quantity of another fluid. However, the existing works are focused on air-conditioning systems or small stand-alone refrigeration systems and no works have been found in relation to condensing units applicable to small-sized refrigeration applications.

Therefore, the present work aims to contribute to the CO_2 refrigerant blends study by providing the results of the experimental evaluation of two CO_2/R-152a blends (95/5% and 90/10% by mass) in a single-stage test rig for commercial purposes at medium temperature level with two refrigeration architectures, the base configuration and one with IHX. The present work, which provides validation of the heat transfer fluids in gas-cooler and evaporator, confirms that the COP of the system can be enhanced, but the experimentally measured increments are lower than the ones predicted theoretically.

2. MATERIALS AND METHODS

2.1. Experimental test plant

The tests were run using a water-to-water single-stage refrigeration plant with a double-stage expansion system, whose scheme is detailed in Figure 1. The compressor is a semi hermetic Dorin CD380H with a displacement of 3.8 $m^3 \cdot h^{-1}$ at nominal speed. Evaporator and gas cooler/condenser are brazed plate counter-current heat exchangers with exchange surface area of 4.794 m^2 and 1.224 m^2, respectively. It incorporates a single-pass double pipe IHX arranged in counterflow with a heat transfer surface area of 0.1194 m^2 which can be connected or disconnected using manual valves. The plant was regulated by using two electronic expansion valves, one that works as a back-pressure valve and one that regulated the flow in the evaporator. When the plant was run in transcritical conditions, the first valve regulated the heat rejection pressure using a custom-made PID controller, while it was left completely open when the plant was running in subcritical conditions. The second valve operated as thermostatic with external equalization. The control of the expansion valve of the evaporator was adjusted to operate with each refrigerant.

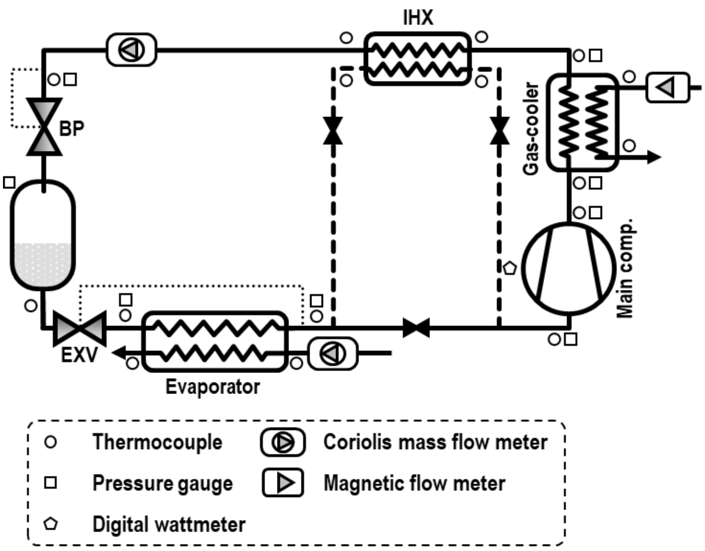

Figure 1. Schematic diagram of the experimental test bench

The plant is fully instrumented to determine its energy performance (see sensors allocation in Figure 1). It incorporates 16 T-type thermocouples (gas-cooler exit and evaporator immersion thermocouples and the rest over the pipe surface), 4 high pressure gauges, 1 medium pressure gauge and 3 low pressure gauges. Refrigerant mass flow rate is measured by a Coriolis mass flow meter located upstream to the back-pressure valve, the volumetric flow of the secondary fluid of the gas-cooler (water) is measured using a volumetric flow meter, while the secondary fluid of the evaporator (water/glycol mixture, 60/40% by volume) mass flow is measured using another Coriolis mass flow meter. The compressor power consumption is registered using a digital wattmeter.

2.2. Selected refrigerant mixtures

The theoretical simulations realized by Xie et al. (2022) and Martìnez-Angeles et al. (2023) concluded that the use of mixtures based on CO_2 and R-152a could improve the energy performance of vapour compression cycles when compared to the use of pure CO_2. The reliability of the results is further supported by the fact that the software Refprop v. 10 (Lemmon E. W. et al., 2018), used to calculate the thermophysical properties of the considered mixtures, includes validated interaction coefficients for the equations of state for such mixtures, fitted from experimental data by Bell and Lemmon (2016). So, R152a was chosen as the second component of the blends experimentally tested.

Another goal considered in order to evaluate which refrigerant was the best option to be used as second component in the mixtures was to keep the direct greenhouse impact of the tested fluids as low as possible. In fact, most of the fluids traditionally used as refrigerants have a high greenhouse warming potential, so the eventual dispersion of these fluids in the environment is very detrimental for the climate change phenomena. The use of R152a, which has a GWP of only 124, as the second component allows to maintain the value of the GWP of the analysed mixtures very low. Another problem due to the use of a fluorinated gas, such as the R152a, is related to the PFAs, which are substances that are suspected of being detrimental for the environment and the human health. Anyway, this problem was not taken into account when the choice of the mixtures was made, because no specific regulation concerning these substances was emitted yet.

The work compares the energy performance of a refrigeration plant obtained by using pure CO_2 and two blends, obtained mixing it with 5% and 10% of mass proportion of R152a, as refrigerants. The p-h diagrams of the three fluids are depicted in Figure 2. The blending of the CO_2 with the R152a, which has a higher critical temperature (113.3°C) and a lower critical pressure (45.2 bar), involves the increase of the critical temperature (10.6 K for 10% R-152a addition), the critical pressure (5.11 bar for 10% R152-a addition), and the latent heat of phase change (for 10% addition: 10.0% more at -10ºC and 15.5% more at 30ºC). Another effect, since the mixture is zeotropic, is the rise of a glide during the phase change (for 10% addition: 13.3K at -10ºC and 6.6K at 30ºC), that could reduce the thermal effectiveness of the evaporator and the condenser. In addition, the density of the investigated blends is lower compared to the pure CO_2 one, so the use of these mixtures implies a reduction in the volumetric cooling capacity (VCC) of the plant.

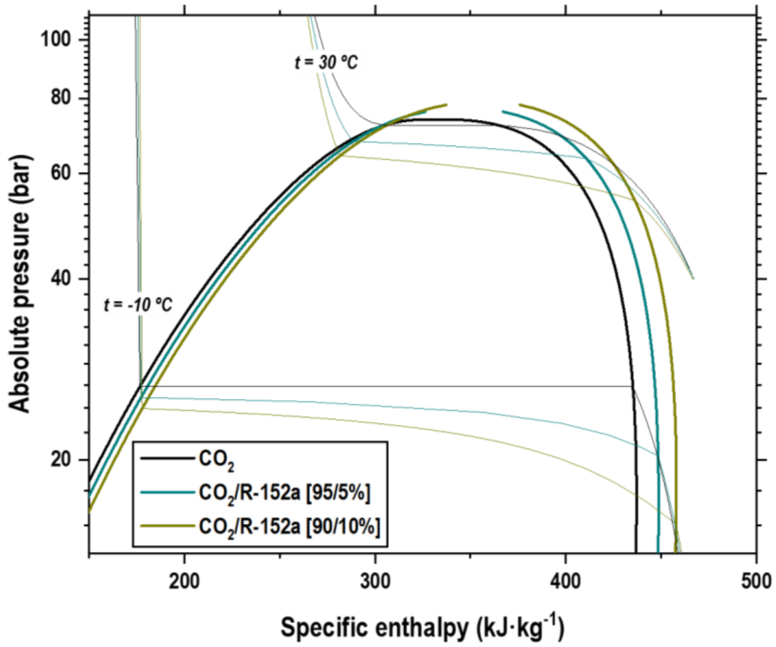

Figure 2 Pressure-enthalpy diagram of the three tested fluids

2.3. Experimental methodology

The plant was charged with 12 kg of every mixture. That amount ensured that at the inlet of the expansion valve the fluid was always in saturated liquid phase in every tested condition. The charged amounts were controlled using a certified mass balance with a measurement error of 5 g.

Every fluid was tested under the same secondary fluids' inlet conditions. While a temperature of 2.5°C and a volumetric flow of 0.7 $m^3 \cdot h^{-1}$ of the 60% water and 40% glycol mixture at the inlet of the evaporator were maintained, the water temperature at the inlet of the gas cooler/condenser at which the plant was tested was 20-25-30-35-40°C, with a volumetric flow that was kept constant at 1.17 $m^3 \cdot h^{-1}$. Because of the maximum allowable temperature at the discharge of the compressor (140°C) and the limits of the capacity of water heat dissipation system, it was not possible to test all the conditions for the mixture CO_2/R152a (95/5%).

When the plant was running in transcritical conditions, the gas cooler pressure was optimized to achieve the maximum COP, and only that value was considered in the comparisons (Nebot-Andrés et al. (2021b)).

3. RESULTS

In this section, the results of the experimental campaign are described. The results are presented regarding the simple cycle in subsection 3.1 and the IHX cycle in subsection 3.2.

3.1. Base configuration

The maximum COPs obtained for each condition and refrigerant are depicted in Figure 3. The COP values calculated by the use of the mixtures were higher than those achieved using pure CO_2 for temperature of the water at the inlet of the gas cooler/condenser greater than or equal to 30°C, while for lower temperature the use of the blends implied an energy efficiency similar or lower than with pure CO_2.

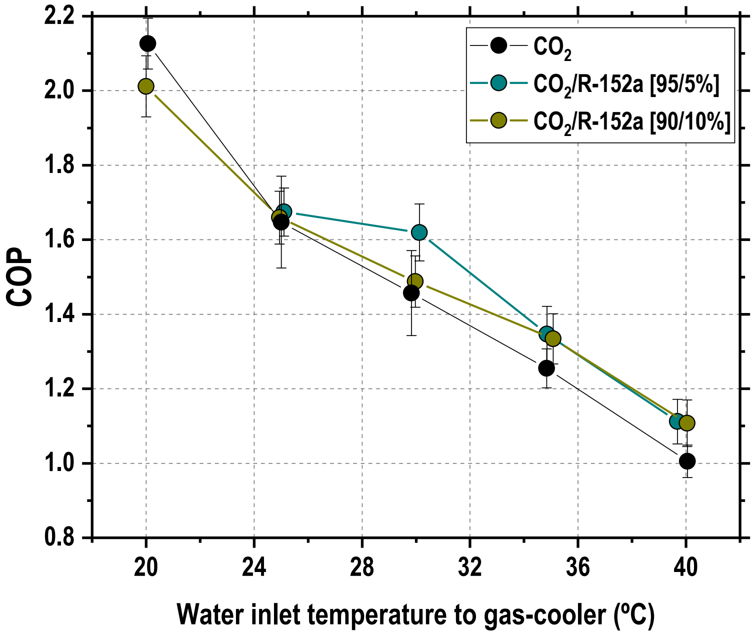

Figure 3 Evolution of the maximum COP for optimal conditions vs condenser/gas-cooler water inlet temperature for Base configuration.

Regarding the cooling capacity, the use of the mixtures always implied a decrease, as it can be seen in Figure 4Figure 4, mainly due to the lower density and volumetric cooling capacity of the blends when compared with the pure CO_2. The cooling capacity reduction was higher for the use of the CO_2/R152a (90/10%) than for CO_2/R152a (95/5%).

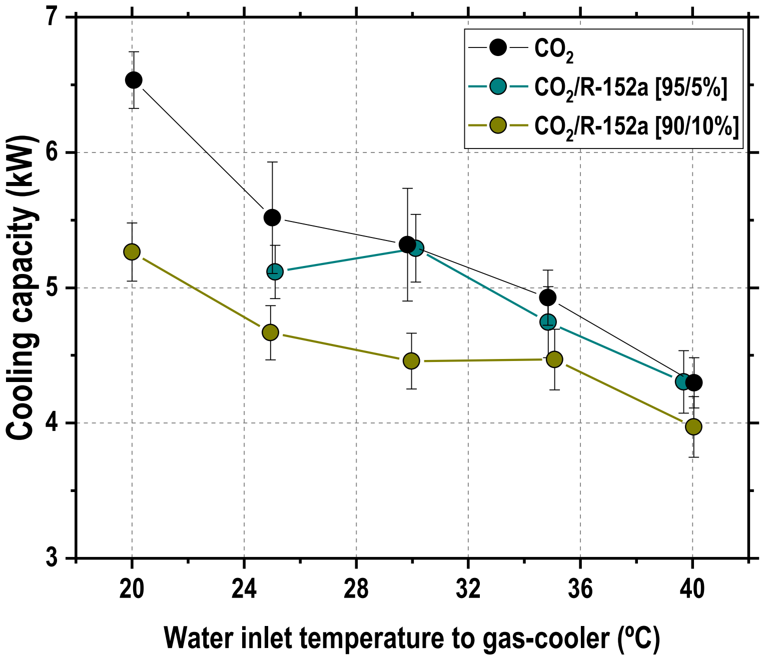

Figure 4. Evolution of the cooling capacity for optimal conditions vs condenser/gas-cooler water inlet temperature for Base configuration

Also the gas cooler/condenser pressures that gave the best COP were decreased when a second component was added to CO_2, as it can be seen in Figure 5, while the temperature of the refrigerant at the compressor discharge was increased, as shown in Figure 6. This effect is mainly due to the decrease of the evaporating pressure when the blends are used instead of the pure CO_2, with the same temperature of the secondary fluid at the inlet of the evaporator. Both phenomena are more pronounced for the blend with the 10% of mass proportion of R152a than for the CO_2/R152a (95/5%) mixture.

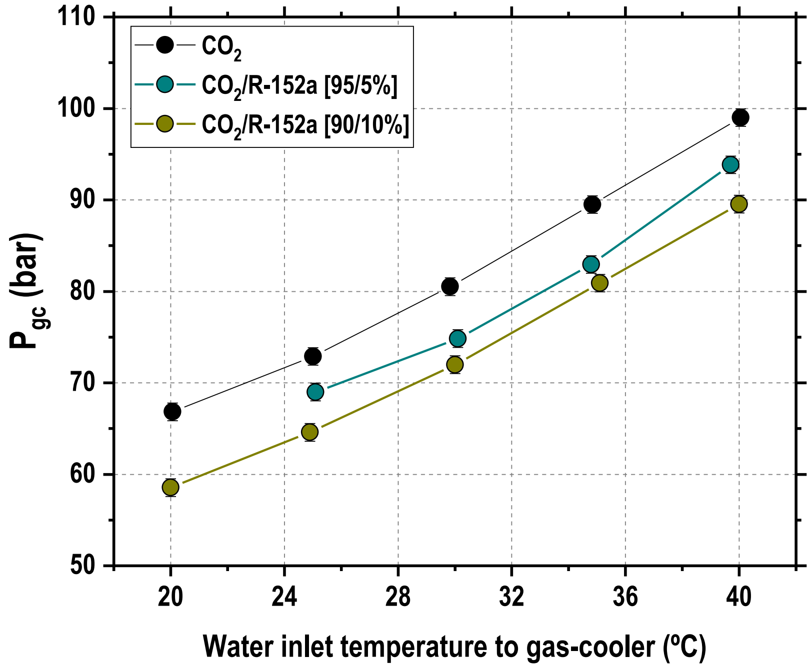

Figure 5. Optimum gas-cooler pressure vs condenser/gas-cooler water inlet temperature for base configuration.

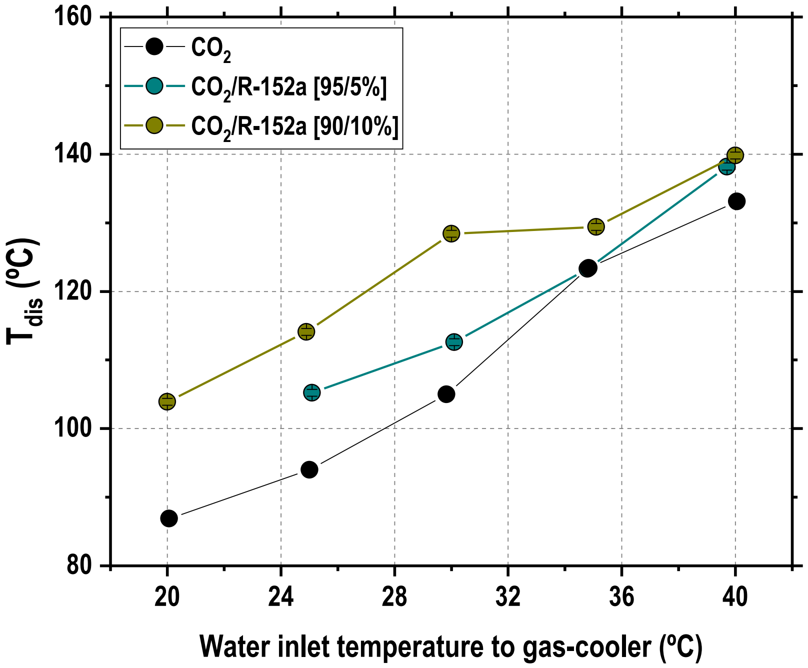

Figure 6. Compressor discharge temperature for optimal conditions vs gas-cooler water inlet temperature for base configuration.

3.2. IHX configuration

The second investigated configuration included a heat exchanger between the fluid downstream the outlet of the gas cooler/condenser and the vapour upstream the suction side of the compressor, that allows to further cool the first and to further heat the second.

In Figure 7 the values of the COP obtained when the three evaluated fluids are used at different water inlet temperature in the gas cooler/condenser are depicted. While for the higher tested temperatures the energy efficiency of the plant was similar, for the temperatures below 30°C the use of the blends instead of pure CO_2 caused the decrease of the COP.

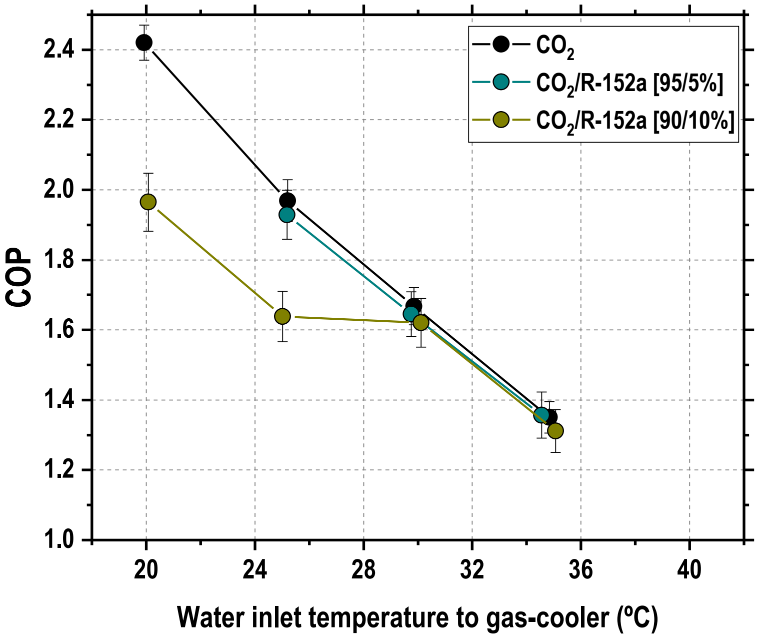

Figure 7. Maximum COP for optimal conditions vs. gas-cooler water inlet temperature for IHX configuration.

As it can be seen in Figure 8, the use of the mixtures implied a significant reduction of the cooling capacity also in the cycle with the IHX. It can be inferred that this effect is mainly due to the relevant reduction of the density of the blends when compared to the pure CO_2, and consequently of the volumetric cooling capacity of the fluid.

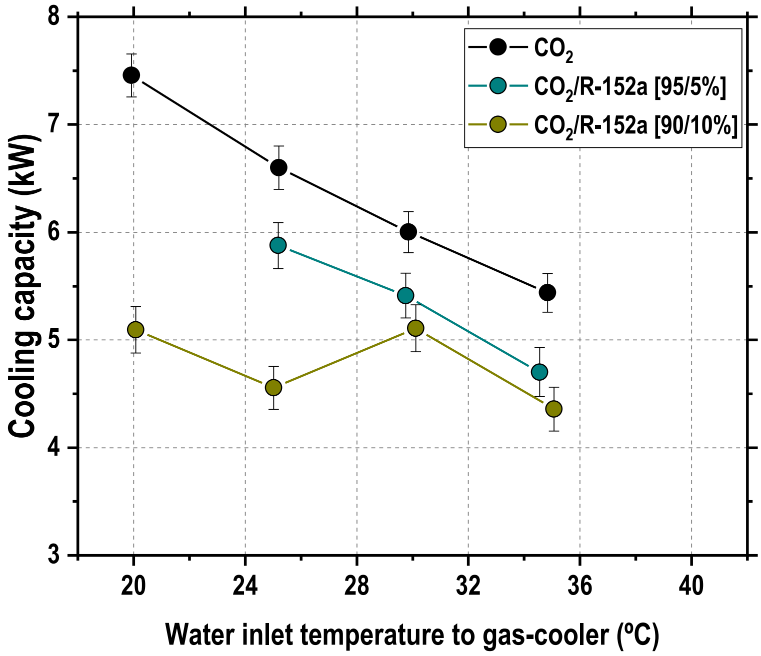

Figure 8 . Cooling capacity for optimal conditions vs. gas-cooler water inlet temperature for IHX configuration

Regarding the optimal gas cooler/condenser pressure and the compressor's discharge temperature, the use of the mixtures in the cycle with IHX implied the same effects observed for the simple cycle. The pressure for which the best COP occurs was decreased, while the discharge temperature in optimum conditions was increased, as it can be seen in Figure 9 and Figure 10, respectively.

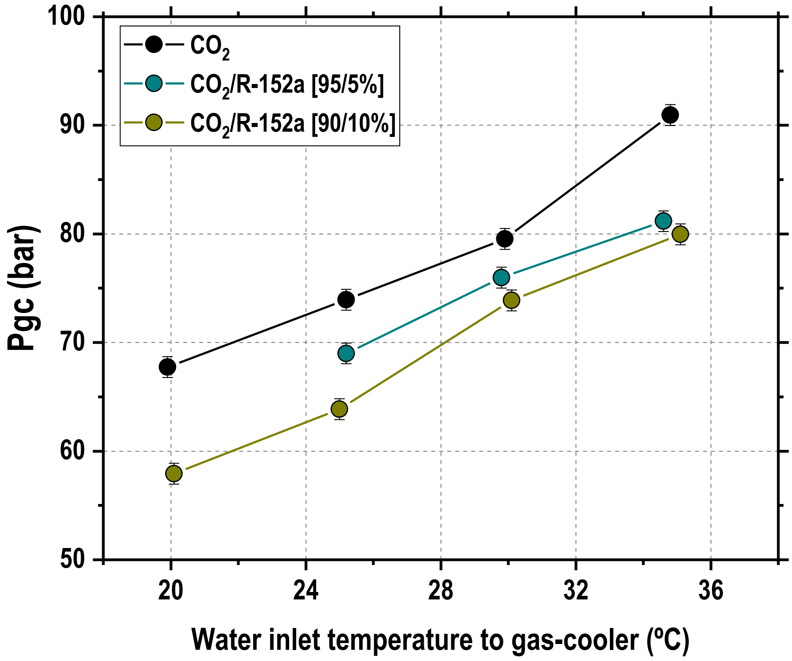

Figure 9. Optimum gas-cooler pressure vs water inlet temperature for IHX configuration.

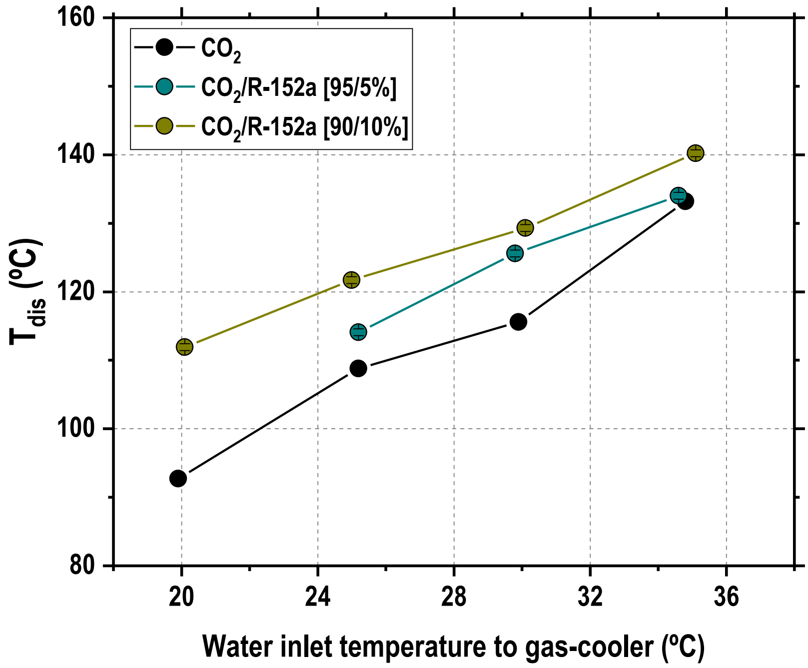

Figure 10. Compressor discharge temperature for optimal conditions vs gas-cooler water inlet temperature for IHX configuration

4. CONCLUSIONS

Two blends CO_2/R152a (90/10%) and (95/5%) were tested in a refrigeration plant with and without an IHX, and the results were compared with those achieved using pure CO_2, at 2.5°C secondary fluid at the evaporator inlet, and 20°C, 25°C, 30°C, 35°C and 40°C for the secondary fluid at the inlet of the gas cooler/condenser. The compressor was always run at nominal speed, and the gas cooler/condenser pressure was optimized at transcritical conditions.
Without IHX, a COP enhancement was measured with the mixture CO_2/R152a (90/10%) compared to pure CO_2 at high heat rejection temperature, namely 6.3% at 35°C gas cooler/condenser water inlet temperature and 10.2% at 40°C. The same happened with CO_2/R152a (95/5%), i.e. 11.2%, 7.3% and 10.2 % at 30, 35 and 40 °C water inlet temperature in the gas cooler/condenser respectively. However, using IHX no significant increases were measured.
At the same time, the use of mixtures implied a decrease in the cooling capacity for all the tested conditions, and an increase in the discharge temperature, while maximum COP is obtained at a lower gas cooler/condenser pressure.
The use of CO_2/R152a gave the best results at high heat rejection temperature with a basic cycle, which is the worst condition in terms of energy performance when compared to traditional fluids. So, the results suggest that such CO_2-based blends can be a way to enlarge the application field for carbon dioxide in replacement of high-GWP refrigerants but need further research.

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NOMENCLATURE

COP	Coefficient of performance	p	Pressure, bar
c_p	Specific heat (kJ/kg K)	P_c	Power consumption, kW
h	Specific enthaply (kJ/kg)	$\dot{Q}_o$	Cooling capacity, kW
$\dot{m}$	Mass flow (kg/s)	VCC	Volumetric cooling capacity
$\dot{V}$	Volumetric capacity (m^3/s)	t	Temperature (K)
bp	Back pressure valve	*l*	Low pressure
dis	Compressor discharge	*o*	Evaporator
g	Glycol + water mixture	*out*	outlet
h	High pressure side	ref	refrigerant
in	Inlet	sf	Secondary fluid
ihx	Internal heat exchanger		

REFERENCES

Aprea, C., de Rossi, F., Mastrullo, R., 1997. The uncertainties in measuring vapour compression plant performances. Measurement 21, 65-70.

ATMOsphere, 2022. Natural Refrigerants: state of the industry. Commercial and industrial refrigeration in Europe.

Bell, I.H., Lemmon, E.W., 2016. Automatic Fitting of Binary Interaction Parameters for Multi-fluid Helmholtz-Energy-Explicit Mixture Models. Journal of Chemical & Engineering Data 61, 3752-3760.

Catalán-Gil, J., Llopis, R., Sánchez, D., Nebot-Andrés, L., Cabello, R., 2019. Energy analysis of dedicated and integrated mechanical subcooled CO 2 boosters for supermarket applications. International Journal of Refrigeration 101, 11-23.

D'Agaro, P, Coppola, M.A., Cortella, G. 2021. Effect of dedicated mechanical subcooler size and gas cooler pressure control on transcritical CO_2 booster systems. Applied Thermal Engineering Volume 1825 January 2021 Article number 116145

European Commission, 2014. Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006.

Gullo, P., Hafner, A., Banasiak, K., 2018. Transcritical R744 refrigeration systems for supermarket applications: Current status and future perspectives. International Journal of Refrigeration 93, 269-310.

John Bush, Mohamed Beshr, Vikrant Aute , Reinhard Radermacher, 2017. Experimental evaluation of transcritical CO_2 refrigeration with mechanical subcooling. Science and Technology for the Built Environment, 1-13.

Karampour, M., Sawalha, S., 2018. State-of-the-art integrated CO_2 refrigeration system for supermarkets: A comparative analysis. International Journal of Refrigeration 86, 239-257.

Kumar, K., Kumar, P., 2019. Analysis of Propane + CO_2 mixture as a working fluid in a vapor compression refrigeration system., 8th Conference on Ammonia and CO_2 Refrigeration Technology. Proceedings: Orhid, North Macedonia, , 2019.

Lata, M., Gupta, D.K., 2020. Performance evaluation and comparative analysis of trans-critical CO_2 booster refrigeration systems with modified evaporative cooled gas cooler for supermarket application in Indian context. International Journal of Refrigeration 120, 248-259.

Lemmon E. W., I.H., B., L., H.M., O., M.M., 2018. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology.

Martínez-Angeles, M., Sicco, E., Toffoletti, G., Nebot-Andrés, L., Sánchez D., Cabello R., Cortella, G., Llopis, R., 2023. Evaluation of CO_2-doped blends in single-stage with IHX and parallel compression refrigeration architectures. International Journal of Refrigeration.

Moffat, R.J., 1985. Using Uncertainty Analysis in the Planning of an Experiment. Journal of Fluids Engineering 107, 173-178.

Nebot-Andrés, L., Calleja-Anta, D., Fossi, C., Sánchez, D., Cabello, R., Llopis, R., 2022. Experimental assessment of different extraction points for the integrated mechanical subcooling system of a CO_2 transcritical plant. International Journal of Refrigeration 136, 8-16.

Nebot-Andrés, L., Calleja-Anta, D., Sánchez, D., Cabello, R., Llopis, R., 2021a. Experimental assessment of dedicated and integrated mechanical subcooling systems vs parallel compression in transcritical CO_2 refrigeration plants. Energy Conversion and Management, 115051.

Nebot-Andrés, L., Sánchez, D., Calleja-Anta, D., Cabello, R., Llopis, R., 2021b. Experimental determination of the optimum intermediate and gas-cooler pressures of a commercial transcritical CO_2 refrigeration plant with parallel compression. Applied Thermal Engineering, 116671.

Purohit, N., Sharma, V., Sawalha, S., Fricke, B., Llopis, R., Dasgupta, M.S., 2018. Integrated supermarket refrigeration for very high ambient temperature. Energy 165, 572-590.

Sánchez, D., Cabello, R., Llopis, R., Catalán, J., Nebot, L., Calleja, D., Gil, E., 2019. Energy improvements in a stand-alone transcritical refrigeration system using a low-GWP mixture of CO_2/R1270, Refrigeration Science and Technology, pp. 2633-2640.

Sánchez D., Calleja-Anta, D., Nebot-Andrés, L., Catalán-Gil, J., Llopis. R., Cabello, R., 2020. Experimental analysis of alternative blends of refrigerants for CO2 transcritical refrigeration., VIII Ibero-american congress on refrigeration sciences and technology, CYTEF 2020, Public Universtity of Navarra, Spain.

Söylemez, E., Widell, K.N., Gabrielii, C.H., Ladam, Y., Lund, T., Hafner, A., 2022. Overview of the development and status of carbon dioxide (R-744) refrigeration systems onboard fishing vessels. International Journal of Refrigeration 140, 198-212.

Tobaly P., Terrier M. F., Bouteiller P., 2018. CO_2 + propane mixture as working fluid for refrigeration in hot climates. Experimental results of energy efficiency tests., 13th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2018). Proceedings. Valencia, Spain.

Vaccaro, G., Milazzo, A., Talluri, L., 2022. Thermodynamic assessment of trans-critical refrigeration systems utilizing CO_2-based mixtures. International Journal of Refrigeration.

Xie, J., Wang, J., Lyu, Y., Wang, D., Peng, X., Liu, H., Xiang, S., 2022. Numerical investigation on thermodynamic performance of CO_2-based mixed refrigerants applied in transcritical system. Journal of Thermal Analysis and Calorimetry 147, 6883-6892.

Yu, B., Wang, D., Liu, C., Jiang, F., Shi, J., Chen, J., 2018. Performance improvements evaluation of an automobile air conditioning system using CO_2-propane mixture as a refrigerant. International Journal of Refrigeration 88, 172-181.

Zhao, Z., Luo, J., Song, Q., Yang, K., Wang, Q., Chen, G., 2022. Theoretical investigation and comparative analysis of the Linde-Hampson refrigeration system using eco-friendly zeotropic refrigerants based on R744/R1234ze(Z) for freezing process applications. International Journal of Refrigeration.