Experimental comparison between R134a/R744 and R438A/R744 (drop-in) cascade refrigeration systems based on energy consumption and greenhouse gases emissions

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Abstract
This experimental study evaluates the energy performance and climatic changes of a cascade cooling system operating with the R134a/R744 pairs (cooling capacity of 4.5-6 kW) and R438A/R744. In both cases, the low-temperature refrigerant, R744, operated under subcritical conditions. The experimental apparatus basically consists of two vapor-compression cycles coupled by a plate cascade condenser. Two operational variables, from R744 cycle, were controlled: the degree-of-superheat and the compressor frequency. The experiment was initially assembled to pair R134a/R744. Subsequently, the R134a refrigerant charge in the high-temperature cycle was replaced by R438A, on a drop-in basis. The two systems, R134a/R744 and R438A/R744, were compared for similar cooling capacities and cold chamber air temperatures. Results showed that the energy consumption of the high-temperature compressor, operating with R438A, was higher than R134a for all tests. As a result, the COP values for R438A/R744 were 30% lower than those for R134a/R744. The greenhouse gases emissions of the two systems were evaluated using the total equivalent warming impact factor, TEWI, whose value for the R438A/R744 pair was approximately 29.5% higher, compared with R134a/R744. Since R438A was originally designed to substitute R22, a few comparative tests were carried out with the latter, always with R744 as the low-temperature cycle working fluid.

Keywords
cascade refrigeration, drop-in, R134a, R438A, R744
INTRODUCTION

To counter global warming and greenhouse gases emissions, the industry has been striving to reduce the environmental impact on refrigeration systems. Refrigerants, which naturally play an important role in such impact, have evolved over the years to comply with environmental regulations. Currently, the direct contribution of refrigerants to the greenhouse effect is widely known. It is quantified by the GWP factor, defined by the mass of CO₂ that would produce the same impact for 100 years on global warming as the release into the atmosphere of a single unit (kg) of a given substance. Likewise, the destruction of the ozone layer, associated with CFCs and HCFCs (in which R22 is included), is quantified by the ODP index.

Although HFCs (current synthetic refrigerants) have zero ozone depletion potential, ODP = 0, they present a high potential for global warming. In some cases, the GWP of these gases is larger than that of HCFCs. Not surprisingly, natural fluids such as hydrocarbons, ammonia, and carbon dioxide with ODP = 0 and very low GWP have been regarded as possible solutions to these issues. Climate change has encouraged the refrigeration community to look for some of the so-called "first-generation refrigerants". Notwithstanding their toxicity or flammability, refrigerants such as ammonia and hydrocarbons can be considered environmentally benign as far as ozone depletion and the greenhouse effect are concerned. The revival of carbon dioxide (CO₂), another refrigerant of this group, low toxic and nonflammable, used in industrial and maritime refrigeration, was first proposed by Lorentzen. In environmental terms, the R744 refrigerant has a zero ODP and a unit GWP which makes it a good candidate for residential and commercial applications. In addition, carbon dioxide is nontoxic, nonflammable, and inexpensive, all attractive features compared with synthetic refrigerants (typically HFCs and HFC blends). R134a refrigerant is, of course, an HFC with zero ODP and, according to AR4 (Assessment Report 4) of the Intergovernmental Panel on Climate Change, the GWP equivalent value for 100 years for this refrigerant is 1430. It has emerged after years of research and testing, to replace R12. It is nonflammable and has acceptable levels of toxicity and is classified as A1 by ASHRAE 34.4

By its turn, R438A refrigerant is also a hydrofluorocarbon blend (R32, R-125, R134a, R600, and R601a; 8.5/45.0/44.2/1.7/0.6 wt%, respectively) with a GWP of 2264. Refrigerant R438A is a non-ozone-depleting refrigerant that can be used to retrofit R22 (due to similar pressure-temperature-enthalpy characteristics) in existing direct expansion (DX) refrigeration and air conditioning systems. According to Allgood and Lawson, R438A refrigerant operates with cooling capacities and COPs similar to R22, equally similar condensing and evaporating pressures but with lower compressor discharge temperatures. This blend has an ASHRAE A1 safety rating (nonflammable, low toxicity) and does not need a re-rating or safety reclassification of the retrofitted equipment.

LITERATURE SURVEY

Refrigerant R438A, together with R404A, R410A, R32, R290, and R1270, was tested as an alternative to R22, by Antunes and Bandarra Filho, in a single vapor compression refrigeration cycle with the evaporating temperature set at −15°C, −10°C, and −5°C. Regarding cooling capacity and COP, hydrocarbons and R32 performed better than R22. Refrigerants R1270 and R290 had the lowest environmental impact (TEWI), while R404A, the highest. Refrigerant R438A was the one that best fulfilled the drop-in role, ie, it returned practically the same original saturation conditions in the heat exchangers. Authors considered it a "near drop-in" refrigerant for R22. The coefficient of performance was comparatively better, by a small amount, for lower cooling capacities.

Panato et al evaluated alternative refrigerants (R1270, R438A, R404A, and R134a) as a drop-in of a refrigeration system running on R22. The comparison was conducted by changing only the lubricating oil (when necessary) and the refrigerant charge, the latter to ensure a proper operation of each system. They concluded that among all conditions and coolants tested, refrigerant R438A, despite its lower cooling capacity, was the best alternative to direct replacement of R22 in a system operating with a scroll compressor. They were based on the observed range of operation and coefficient of performance (COP). With R438A, the system operated in a wider range of compressor frequencies, electronic expansion valve openings, and evaporation temperatures, while the same lubricating oil was maintained.

Despite increasingly restrictive European Commission legislation on the use of HFC gases, most supermarket refrigeration systems still rely on the use of R134a and R404A refrigerants. Synthetic refrigerants such as R404A, R507A, and R22 remain the most common refrigerants used in direct-expansion supermarket systems, the latter in developing countries only. Average leak rates during use in these systems are estimated to be within 15%-35% of the total refrigerant charge, with the lower rates to be found in modern facilities. A recent work reports on the analysis of three Swedish supermarkets using typical HFC refrigeration systems. A combination of field measurements and modelling predictions showed that, for outdoor temperatures below 24°C, R744 systems have higher COP, compared with HFC systems.
Carbon dioxide has a great potential for application in supermarkets\(^{11}\) despite being fluid with high working pressures. It has a high critical pressure (73.8 bar) and a low critical temperature (30.97°C), which makes the cascade refrigeration alternative a feasible solution: low evaporating temperatures in the cold-medium coil are obtained with a noncritical R744 vapor compression cycle; heat rejection of the R744 cycle is kept below the critical temperature by means of another vapor compression cycle, operating “on top” of it, and running, like in the present work, with R134a or R438A. The positive side of a high operating pressure is that a high vapor density is attained and, therefore, a high volumetric refrigerating capacity. As a matter of fact, the volumetric capacity of R744 is 22.545 kJ/m\(^3\) at 0°C, which is 3-10 times larger than other halogenated refrigerants.\(^{11}\)

The main characteristics of the refrigerants involved in the present work are presented in Table 1.

Although cascade vapor compression refrigeration systems have been reported in use since the 1930s,\(^{12}\) a limited number of experimental studies of such systems, on prototypes or laboratory setups, are found in the literature. Table 2 summarizes a review of the recent literature on experimental works on cascade vapor compression systems, with publications spanning over a period of nearly a decade. Except for a heat pump,\(^{13}\) for water heating purposes, and two setups for low-temperature refrigeration,\(^{14,15}\) papers on refrigeration\(^{16-24}\) report on evaporating temperatures (of the low-temperature cycle) within the range of −30°C and −50°C, which is typical of operation of commercial and industrial refrigeration plants. Exceptionally, higher evaporating or heat source temperatures are also found, such as −5°C,\(^{16} 2^\circ\text{C},\) −20°C,\(^{17}\) and −8°C.\(^{18}\) For most of the refrigeration cases, the condensing temperature (of the high-temperature cycle) remained between 25°C and 50°C. Only Winkler et al\(^{18}\) report a condensing temperature as low as 10°C. Cooling capacities of the refrigeration systems remained below 10 kW, except for Bingming et al,\(^{19}\) with 161-263 kW, and Winkler et al,\(^{18}\) 10-22 kW.

Compressors of all types (hermetic, semi-hermetic, rotary, scroll, variable speed) have been used, as they were selected to suit the specifications of each refrigerant. For their versatility and compactness, most cascade condensers are of the plate type. And, as far as expansion devices are concerned, even though thermostatic expansion valves (TXV) have been used in the HT cycle\(^{18,19}\) and ejectors in both circuits,\(^{20}\) electronic expansion valves seem to be more appropriate as they inherently provide a better control, an important issue for cascade systems.\(^{21-24}\) It appears that the HT EEV plays an important role in indirectly controlling the evaporating temperature of the HT cycle, also called the coupling temperature, which has been a key variable in the optimization of the cascade global COP, as reported by, for example, Getu and Bansal\(^{25}\) and Sachdeva et al.\(^{26}\)

One observes, from Table 2, that all cascade refrigeration systems employ R744 as the low-temperature refrigerant. In line with the discussed above, lower energy consumption reduced environmental impact, and equipment compactness\(^{23}\) are the main reasons for this choice. It should be reminded that the use of R744 in supermarket applications involves different solutions, including cascade systems, conventional, or with parallel compression, a R744 refrigeration system with mechanical subcooling,\(^{27}\) R744 booster refrigeration systems,\(^{28}\) transcritical or subcritical cycle operation, discharge gas cooler (when temperature exceeds the outdoor temperature), liquid-line–suction-line heat exchanger,\(^{21}\) etc. For the high-temperature cycle, refrigerant options were NH\(_3\), R134a, and R404A, with two drop-in studies, R134a for R152a\(^{21}\) and for R404A.\(^{17}\) The drop-in performance with R404A was inferior to that of the base fluid,\(^{17}\) whereas Cabello et al\(^{21}\) reported similar energy performances with R134a or drop-in R152a.

### TABLE 1  Fluids’ characteristics

|          | R744 | R134a | R438A |
|----------|------|-------|-------|
| GWP      | 1    | 1430  | 2264  |
| ODP      | 0    | 0     | 0     |
| Molar mass (kg/kmol) | 44.0 | 102.0 | 99.1  |
| Normal boiling point (°C) | −78.4 | −26.1 | −42.33 |
| Critical pressure (bar) | 73.8 | 40.6  | 43.0  |
| Critical temperature (°C) | 31.1 | 101.1 | 85.3  |
| Critical density (kg/m\(^3\)) | 467.6 | 511.9 | 510.5 |
| Temperature glide (°C) | -    | -     | 3-4   |
| ASHRAE Standard 34 – Safety classification | A1 | A1 | A1 |

Source: refrigerant manufacturers.

### 3  JUSTIFICATION

Although refrigerant R438A was originally devised to work as a R22 drop-in substitute, its application as a R134a drop-in, with a R134a compressor, as it will be shown in the present work, proved to be technically possible (as far as temperatures and pressures are concerned). The aim of this work is to analyze refrigerant R438A substituting R134a as the high-temperature cycle refrigerant of a cascade system. Table 2 shows that, in most experimental studies of cascade cooling cycles, R134a was the HTC refrigerant. On the other hand, no record of any system operating with R22 as HTC was observed.

An overall observation of Table 2 reveals that to the authors’ knowledge: (a) No experimental work has yet been
| Authors, year | Refrigerant pair (HT/ LT) | Drop-in? | Cooling capacity (kW) | COP (−) | TEWI (tonCO2) | Heat source/heat sink | Heat source temperature (°C) | Heat sink temperature (°C) | Compressor type | Cascade condenser type | Expansion devices |
|--------------|---------------------------|----------|-----------------------|---------|-------------|----------------------|---------------------------|---------------------------|----------------|---------------------|-------------------|
| Sánchez et al,17 2017 | R134a/R744 | - | not available | not available | - | liquid-to-air (direct) | −35 (cabinet temperature) | 25, 35, 45 (cond) | semihermetic | brazed plate | EEV |
| Cabello et al,21 2017 | R134a/R744 | base | 4.2-7.1 | 0.901-0.597 | - | liquid-to-liquid | −40, −35, −30 | 30, 40, 50 | HT: VSSH | LT: SH | brazed plate |
| Queiroz et al,17 2016 | R404A/R744 | yes, R-404A | 2.16 to 3.00 | 0.80-0.95 | - | liquid-to-liquid | −40, −30 | 30- 50 | HT: VSSH | LT: SH | brazed plate |
| Sanz-Kock et al,22 2014 | R134a/R744 | - | 4.5-7.5 | 1.05-1.65 | - | liquid-to-liquid | −30 (evap) | 40 (cond) | HT, LT: SH | brazed plate | TXV or EEV |
| da Silva et al,23 2012 | R404A/R744 | - | 9.8 | - | - | air-to-air or air-to-water | −33 to −8 | https://doi.org/10.0 to 48.9 (cond) | Variable capacity compressors | brazed plate | LT, HT: TXV |
| Bingming et al,19 2009 | R717/R744 | - | 161-263 | 1.41-1.14 | - | brine-to-water | −30 to −50 (evap) | 40 (cond) | Twin screw-type | shell-and-tube | Throttle valves |
| Dopazo and Fernández-Seara,20 2011 | R717/R744 | - | 8.07-9.45 | 0.95-1.80 | - | (plate freezer)-to-air | −50 − 45 | 30 (cond) | LT: SH | brazed plate | LT: ejector |
| Winkler et al,18 2008 | R404A/R744 | - | 10.22 | - | - | glycol-to-water | −33 to −8 | Variable capacity compressors | brazed plate | LT, HT: TXV |
| Sawalha,24 2008 | R717/R744 | - | MT: 16.6 | LT: 7.4 | 2.2 | - | Air-to-water | MT: 8 | 33 | LT: VS scroll | plate type | LT: EEV |
| Present work, 2019 | R134a/R744 | Base | 4.6-5.6 | 1.8-2.1 | 85 | air-to-air | −17.7 to −2.9 | 27 to 33 | HT: VSSH | brazed plate | HT: EEV |
| Heat Pump | R438A/R744 | yes, R438A | 4.5-5.2 | 1.4-1.7 | 110 | air-to-water (heat pump) | −17 to 8 (evap) | 50 to 65 (cond) | Twin rotary | brazed plate | EEV |

(Continues)
carried out with R438A, either as the base or drop-in HT refrigerant, for a cascade refrigeration cycle; (b) No analysis of the environmental impact of cascade refrigeration systems has been carried out, to date, based on experimental data.

By performing an experimental comparison between R744/R134a and R744/R438A (drop-in) cascade refrigeration systems, based on energy and greenhouse gases emissions, the present work aims at filling these gaps.

At first glance, a comparison of the GWP values of the refrigerants R134a and R438A, 1430 and 2264, respectively, would discourage the use of R438A as the drop-in of R134a, and, therefore, the purpose of this study. However, it should be considered that other factors, refrigerant load, and energy consumption, not yet reported in the literature for these conditions, should also be considered in the determination of the environmental impact of the system. Since not even simulation results are available in the literature, one expects that the experimental data presented here may provide a preliminary idea of the operational (cold-room temperature and refrigerating capacity), energy (consumption), and environmental (global warming impact) performance of the R438A/R744 refrigerant pair in cascade refrigeration systems.

Moreover, considering that:

a. Refrigerant R438A is still commercially available from two major manufacturers.

b. Phasedown of HFCs will take place gradually, with, for example, Article 2 countries reducing HFC production down to 15 percent of baseline levels by 2036, and China (an Article 5, Group 1 country) agreeing to peak production and consumption of HFCs by 2024, with reductions ultimately reaching 80% by 2045.29

It is not unconceivable that, during this period (present date, 2021, to 2045), local circumstances may lead to an unorthodox R438A/R744 drop-in solution for a cascade refrigeration system. By then, the existence of an archival paper contributing to the evaluation of the pros and cons of such decision, from the energy and environmental points of view, would be useful.

4 | EXPERIMENTAL APPARATUS AND WORKING FLUIDS

Figure 1 depicts the experimental setup, divided into two cycles: the R744 or low-temperature cycle (LT), and the R134a (later replaced by R438A) or high-temperature cycle (HT). The low-temperature cycle consists of a variable speed compressor for R744 (Bitzer, reciprocating semi-hermetic, two-cylinder, bore-stroke of 30 × 13.2 mm,
OCTAGON, model 2MSL-07K-20D, nominal displacement of 1.96 m³/h at 1750 rpm, an electronic expansion valve (CAREL, model E2V09B) and a direct expansion air-source evaporator (Guntner, model CDL 0168.0X7A CO₂, equipped with fans VT01173U) inside a cold room (2.3 m × 2.6 m × 2.5 m chamber, insulated with 150-mm thick polyurethane, with density of 38 kg/m³ and thermal conductivity of 0.028 W/(mK). Refrigerant R744 leaves the compressor as superheated vapor and is condensed at a brazed plate heat exchanger, known as cascade condenser (SWEP, model B25Tx26H/1P, 26 plates), and then stored in a liquid tank. From the liquid tank, as saturated liquid, it expands through the expansion valve, into the evaporator unit. Leaving the evaporator, it passes through the internal liquid-line-suction-line heat exchanger (SWEP, model B5x4H/1P, four-plate brazed plate, streams in counter-flow), where the degree of superheat increases and, finally, it returns to the compressor.

The HT cycle consists of a compressor for R134a (Bitzer, reciprocating semihermetic, two-cylinder, bore-stroke of 55 × 39.3 mm, OCTAGON, model 2CC-4.2Y-20D, nominal displacement of 19.6 m³/h at 1750 rpm), an air-cooled condenser (Bitzer, model LH84-30) and an electronic expansion valve (CAREL, model E2V35B). Figure 2 depicts the experimental bench and Figure 3 is a view of the cold room. The cascade heat exchanger used was a brazed plate type, countercurrent type (model B25Tx26H/1P from the SWEP manufacturer) with dimensions of 119 × 526 × 12.25 mm of 26 plate stainless steel 304, with a maximum flow volume of 9 m³/h and a weight of 2.13 kg. In the case of the intermediate heat exchanger, it was of the brazed plate type, countercurrent (model B5x4H/1P from the manufacturer SWEP) with dimensions of 72.50 × 187.5 × 13.61 mm of 4-plate stainless steel 316, with a maximum flow volume of 4 m³/h and a weight of 0.30 kg.

**FIGURE 1** Schematic diagram of the cascade system with location of main temperature or pressure sensors
The system was properly instrumented, with piezo-resistive pressure transducers (ZURICH, model PSI.420, measurement uncertainty of 25 kPa) and PT100 resistance temperature transducers (ADD Therm, model PT100-A70-001-L-X50-3F-X0-X30, measurement uncertainty of 0.15°C) installed at relevant points of the system. Coriolis flow meters, placed at the liquid line of each one of the high- and low-temperature cycles (Metroval, uncertainty of 0.07%, models RHM03-4FS1PN and RHM06-1FS1SS, respectively), measure refrigerant mass flow rates. The power consumption of each compressor was measured, and the uncertainty was 0.003 kW. Location of sensors, as displayed in Figure 1, was as follows: (1) LT compressor discharge temperature; (2) LT condensing pressure; (3) LT liquid temperature; (4) LT evaporating pressure; (5) LT evaporator outlet temperature; (6) LT compressor suction temperature; (7) HT compressor discharge temperature; (8) HT condensing pressure; (9) HT liquid temperature; (10) HT evaporating pressure; (11) HT compressor suction temperature.

For the R134a circuit, a refrigerant charge of 3.9 kg was used, an amount that returned correct operating conditions for the LT Compressor, which means a proper degree of useful superheating, no vapor at the HT cycle liquid line, and absence of liquid starvation at the HT and LT evaporators. Likewise, for the drop-in refrigerant, R438A, 90% of the original system charge, ie, 3.5 kg, was applied; this value was adopted following technical procedures recommended by the compressor manufacturer. As the R744 circuit has a liquid reservoir, a higher charge of refrigerant, 23.0 kg, was needed. Finally, the high-temperature cycle drop-in procedure was planned to provide similar refrigerating capacities and cold room air temperatures, with either R134a or R438A.

All refrigerant properties were calculated by EES (Engineering Equation Solver), version 10.103, based on the standard reference state of the International Institute of Refrigeration. Figure 4 shows the superimposed P-h diagrams of R134a/R744 and R438A/R744 pairs, respectively. Evaporation and condensation isotherms and thermodynamic states from a typical experimental run (compressor frequencies of 65 Hz, for R744, and 60 Hz, for R134a, a 10 K degree of superheating for R744, cold-room internal electric resistance of 3.0 kW, and cold-room temperature of −13.6°C) are presented. One observes that
R744 operating pressures are much higher than those of R134a or R438A.

The oil-refrigerant miscibility issue should not be overlooked, of course, in a drop-in procedure. Refrigerants R438A and R134a are compatible with POE (Polyol ester) lubricant so that no change of oil type was necessary during drop-in. For the R744 system, POE lubricant (Bitzer BSE 85K) especially developed to have good miscibility with refrigerant carbon dioxide, under low temperatures and high pressures, was used.

5 | EXPERIMENTATION AND DATA REDUCTION

A period of approximately 5 hours was needed for a steady-state condition to be reached. This condition was observed from measured values of pressure, temperature, and mass flow sensors. The amount of oil mixed into refrigerant, bubbles across the flow meter and instrument noise related to the data acquisition system impeded the system rapid stability. The experimental setup was only
considered to be operating in steady state when the variation of the measured values did not exceed the value of three times the standard deviation of the data sample, for a testing period of ten minutes. Compressors discharge temperatures and air temperature in the cold chamber were the last parameters to reach steady-state condition. Experimental data were collected every 10 minutes after the onset of steady state.

Two basic parameters had their values varied during experiments: the degree of superheat and compressor frequency in the R744 circuit. A bench of electrical resistors, dissipating thermal power into the cold room, ranged from 1.5 to 3.5 kW and emulated the thermal load of the system. The condensing temperature of the low-temperature cycle varied in response to the degree of superheat imposed at the high-temperature evaporator, emphasizing the importance of the cascade condenser in the system overall performance. Tests started with the R134a/R744 pair, followed by the drop-in combination, R438A/R744.

The following directives guided the experimental tests: (a) the R744 evaporator operated with a useful superheat of 5 K, 10 K, and 15 K; (b) LT compressor frequencies ranged from 50, 55, 60 to 65 Hz, attained by means of a frequency inverter; (c) the HT cycle compressor (R134a or R438A) operated at a fixed frequency of 60 Hz; (d) the degree of useful superheat in the EEV HT was adjusted to 27 K, so that the resulting LT condensation temperature was maintained around −9.0°C and, therefore, subcritical. By its turn, for refrigerant R438A, the EEV HT operated with a superheating of 10 K, aiming at higher R438A evaporating temperatures, which would lead to higher R744 evaporating and condensing temperatures, more in line with those obtained with the R438A/R744 pair; (e) The LT cycle operated at a fixed degree of subcooling of 0 K, ie, no subcooling.

The cooling capacity of the system, \( \dot{Q}_{\text{SYST}} \), was calculated assuming steady-state condition and applying the energy balance to the evaporator control volume encompassing refrigerant R744 only.

\[
\dot{Q}_{\text{SYST}} = \dot{m}_{LT}(\Delta h_{\text{evap}}) \tag{1}
\]

Where \( \dot{m}_{LT} \) represents the R744 mass flow rate and \( \Delta h_{\text{evap}} \) is the refrigerant specific enthalpy difference across the evaporator. The COP of the cascade system is the ratio between the cooling capacity and the sum of the power consumption of the two compressors. The energy consumption of the heat exchangers fans (HT condenser and LT evaporator) was not computed in the COP calculation.

\[
\text{COP} = \frac{\dot{Q}_{\text{SYST}}}{W_{LT} + W_{HT}} \tag{2}
\]

Environmental performance evaluation was carried out by parameter TEWI (Total Equivalent Warming Impact), considering both direct and indirect impacts, the first one related to greenhouse gases released during the lifetime of the equipment, and the latter associated with emissions due to the lifetime consumption of electrical energy.\(^{32}\)

\[
\text{TEWI} = \text{TEWI}_{\text{DIRECT}} + \text{TEWI}_{\text{INDIRECT}} \tag{3}
\]

where:

\[
\text{TEWI}_{\text{INDIRECT}} = \text{GWPL} \cdot mn + \text{GWP} \cdot m(1 - a) \tag{4}
\]

\[
\text{TEWI}_{\text{INDIRECT}} = E \cdot \rho n \tag{5}
\]

The GWP values of R744, R134a, and R438A were taken as equal to 1, 1430, 2264 respectively, and the annual leakage rate, for a centralized system in typical operational condition, was set at 12.5%.\(^{32}\) The economic lifetime was assumed to be 10 years, for each refrigerant.\(^{8}\) Refrigerant recovery rate was assumed to be 70%, for equipment with a refrigerant charge of less than 100 kg.\(^{32}\) A 16-hour cooling demand at 100% was considered and the same operational hours were assumed for both refrigerant circuits. The indirect emission factor was 0.531 kgR744/kWh, based on the intensity of R744 emissions for all electrical generation sectors of the USA.\(^{33}\)

Evaluation and expression of the uncertainties of the measurement results were carried following Taylor and Kuyatt.\(^{34}\)

6 | RESULTS AND DISCUSSION

A comparative analysis of the thermodynamic and environmental performance of the original cascade system, operating with R134a/R744, and the alternative system, R438A/R744, was carried out. Table 3 presents a total of 18 experimental runs. It includes parameters such as the evaporation and liquid line temperatures of the LT cycle (R744), \( T_{\text{EVL}} \) and \( T_{\text{LL}} \), respectively, as well as the cooling capacity and overall COP, with their respective uncertainties. Tests carried out with R22/R744 are shown in Appendix A.

The thermodynamic comparison assumes that both refrigeration systems, with the original or alternative pair of refrigerants, should perform similarly, as far as refrigeration capacity and cold room air temperature are concerned. Figures 5 and 6 demonstrate such performance similarity. Figure 5 shows the air temperature inside the cold room for both original and drop-in systems; the abscissa axis represents the reference temperature, ie, values for the original system while the ordinate axis represents the drop-in system temperatures. No deviation exceeding
| Systems       | $f_{LT}$ (Hz) | $\Delta T_{SH_{LT}}$ (°C) | $T_{EV_{LT}}$ (°C) | $T_{CD_{LT}}$ (°C) | $T_{H_{LT}}$ (°C) | $\dot{m}_{LT}$ (kg/s) | $\dot{W}_{LT}$ (kW) | $P_{EV_{LT}}$ (bar) | $P_{CD_{LT}}$ (bar) | $CR_{LT}$ (-) | $T_{H_{LT}}$ (°C) | $T_{EV_{LT}}$ (°C) | $T_{CD_{LT}}$ (°C) | $T_{AIR}$ (°C) | $\dot{Q}_{SYS}$ (kW) | COP (-)     |
|--------------|--------------|--------------------------|-------------------|-------------------|------------------|-----------------------|-------------------|--------------------|--------------------|----------------|-------------------|-------------------|-------------------|----------------|-------------------|-------------|
| R134a/R744  | 65.00        | −26.7                    | −9.6              | 84.5              | −9.6             | 0.0202               | 0.690             | 2.00               | 1.9                | 7.9              | 4.2               | 101.0             | −11.4             | 31.0             | −8.5              | 5.57 ± 0.02   | 2.07 ± 0.01 |
| R134a/R744  | 10           | −26.9                    | −9.8              | 81.6              | −9.9             | 0.0178               | 0.670             | 1.90               | 1.8                | 7.7              | 4.3               | 101.0             | −12.7             | 30.1             | −13.6             | 4.83 ± 0.02   | 1.88 ± 0.01 |
| R134a/R744  | 5            | −25.7                    | −8.6              | 79.6              | −8.7             | 0.0184               | 0.680             | 2.00               | 1.9                | 7.9              | 4.2               | 103.0             | −11.4             | 31.0             | −17.7             | 4.85 ± 0.02   | 1.81 ± 0.01 |
| R438A/R744  | 65.00        | −26.5                    | −12.3             | 79.1              | −12.3            | 0.0183               | 0.590             | 3.00               | 2.6                | 14.4             | 5.5               | 102.0             | −14.6             | 34.7             | −8.2              | 5.17 ± 0.02   | 1.44 ± 0.00 |
| R438A/R744  | 10           | −26.7                    | −14.4             | 73.2              | −14.4            | 0.0164               | 0.525             | 2.75               | 2.4                | 12.4             | 5.2               | 94.8              | −16.6             | 28.9             | −13.3             | 4.62 ± 0.02   | 1.41 ± 0.01 |
| R438A/R744  | 5            | −26.3                    | −13.8             | 73.1              | −13.9            | 0.0176               | 0.550             | 2.80               | 2.4                | 13.1             | 5.5               | 99.0              | −16.6             | 31.0             | −18.5             | 4.84 ± 0.02   | 1.45 ± 0.01 |
| R438A/R744  | 60.00        | −27.5                    | −14.8             | 70.3              | −15.0            | 0.0172               | 0.440             | 2.65               | 2.3                | 12.5             | 5.4               | 94.1              | −17.6             | 29.2             | −8.2              | 4.98 ± 0.02   | 1.61 ± 0.01 |
| R438A/R744  | 10           | −26.5                    | −15.9             | 70.8              | −15.9            | 0.0172               | 0.460             | 2.70               | 2.4                | 13.0             | 5.4               | 99.0              | −16.6             | 30.7             | −12.5             | 4.77 ± 0.02   | 1.51 ± 0.01 |
| R438A/R744  | 5            | −25.6                    | −14.5             | 69.2              | −14.6            | 0.0176               | 0.480             | 2.69               | 2.4                | 13.7             | 5.7               | 100.0             | −16.6             | 32.8             | −16.6             | 4.89 ± 0.02   | 1.54 ± 0.01 |
| R438A/R744  | 55.00        | −24.8                    | −15.1             | 68.2              | −15.2            | 0.0176               | 0.425             | 2.65               | 2.3                | 14.2             | 6.2               | 99.0              | −17.6             | 34.2             | −4.9              | 5.10 ± 0.02   | 1.66 ± 0.01 |
| R438A/R744  | 10           | −23.5                    | −13.4             | 70.0              | −13.4            | 0.0164               | 0.450             | 2.80               | 2.5                | 14.2             | 5.7               | 100.0             | −15.6             | 34.2             | −10               | 4.59 ± 0.02   | 1.41 ± 0.01 |
| R438A/R744  | 50.00        | −23.5                    | −15.3             | 66.9              | −15.3            | 0.0154               | 0.385             | 2.65               | 2.3                | 13.9             | 6.0               | 100.0             | −17.6             | 33.4             | −2.9              | 4.47 ± 0.01   | 1.47 ± 0.01 |
10% was found. Figure 6 shows the broad temperature range of the cascade system, working with either R134a or R438A, under different operational conditions and reaching different cooling capacities.

The HT cycle compressor frequency was set at 60 Hz in both cases, with the aim of evaluating the drop-in process by changing only the high-temperature refrigerant cycle. It is also noteworthy that in several countries the nominal frequency is 60 Hz. It would be possible to use a frequency inverter in the high-temperature cycle, however, it was decided to maintain the nominal frequency since practically all cascade refrigeration plants operate without a frequency inverter. It is important to highlight that all tests were performed when the ambient temperature was between 27 and 33°C and the condensing temperature did not vary by more than 2°C during the entire test run.

Tests at 60 and 65 Hz were carried out under degrees of superheating of 5, 10, and 15°C, while tests at 50 and 55 Hz did not achieve the same range of superheating. This was due to physical limitations of the experimental facility, which operated with LT compressor and heat exchangers at limit conditions. It is worth mentioning that, with lower degrees of useful superheat and higher compressor frequencies, the lowest air temperature values are obtained. For example, the original system, operating at $f_{LT} = 65$ Hz and $\Delta T_{SH_{LT}} = 5$°C, reached the minimum steady-state temperature inside the cold room, −17.7°C. The highest temperature was −2.9°C, for the original system at $f_{LT} = 50$ Hz and $\Delta T_{SH_{LT}} = 15$°C. Since the cascade refrigeration system operates with electronic expansion valves for the low- and high-temperature cycles, the degrees of superheat were maintained by means of the valve controllers. The degree of superheat control is performed based on the difference between the temperature measured at the evaporator outlet and the saturation temperature at the evaporation pressure. Thus, in the low-temperature cycle the degree of superheat tested was 5 K, 10 K, and 15 K. For the high-temperature cycle, the superheat was 27 K, precisely to maintain the condensing temperature at −9°C across the entire test range.

The degree of subcooling in the low-temperature cycle is very close to 0 K, as the liquid tank ensures the output of the R744 in the liquid subcooled phase. The degree of subcooling in the high-temperature cycle ranges from 10 to 15 K over the entire test range. Such values are possible due...
to the presence of the intermediate heat exchanger, located between the evaporation line of the low-temperature cycle and the condensing line of the high-temperature cycle.

Figure 6 shows the cooling capacity. Similarly, to Figure 5, the abscissa axis represents the reference cooling capacity, while the ordinate axis, the alternative system under the same control variables, $f_{LT}$ and $\Delta T_{SHLT}$. The original cooling capacity ranged from 4.58 ± 0.01 to 5.57 ± 0.02 kW, demonstrating the applicability of this cascade system for operation under variable thermal load conditions. The highest cooling capacity occurred at the frequency of 65 Hz, operating at 15°C of superheat, for the R134a/R744 system.

The low-temperature mass flow rate, $m_{LT}$, was found to be slightly higher for the R134a/R744 pair, although the R438A/R744 combination allows for a greater enthalpy difference across the evaporator. This effect is linked to the pressure conditions in the cascade heat exchanger, as they promote lower condensation temperatures, $T_{CDLT}$, in the LT cycle. For this reason, the cooling capacities for original and alternative systems are similar.

A performance comparison between systems is presented in Figures 7 and 8. The R134a/R744 system showed an advantage over the retrofit R438A/R744 pair. As stated before, cooling capacities for both systems were similar. However, the HT R438A compressor consumption was higher in all tests, leading to lower COP values for the alternative system. The energy consumption of the R744 compressor in pair with R134a is generally lower than that system working with R438A. This could be explained by the fact that the R744 cycle operates at lower condensing temperatures when working with R438A. This is due to the thermodynamic characteristics of refrigerant R438A, which presented lower evaporation temperatures when compared to R134a. The volumetric cooling capacity, which is higher for R438A, is another condition that explains the reduction in the energy consumption.

The COP of a traditional direct expansion system tends to increase with the reduction of useful superheating. However, in the case of a cascade system, more factors come into play when assessing influences on the COP. Thus, according to Table 3, the HT cycle energy consumption is more relevant to the system COP compared with LT consumption, which decreases with useful superheating reduction.

Refrigerant R744, in pair with R134a, works at a higher compression ratio, which requires more work of its compressor, thus increasing the total energy consumption. The R744 condensing pressures of the original cascade system are greater than that of the alternative system, with R438A. Discharge temperatures of the LT cycle, $T_{DLT}$, for the alternative system, are lower in all situations, leading to better lubrication conditions, thus extending compressor lifetime. Figure 8 shows that R744 discharge temperature is lower in the alternative system. In addition, it can be observed that the discharge temperature decreases with the reduction of two parameters of the LT cycle: (a) compressor frequency and, (b) useful degree of superheating.

According to Table 3 and Figure 9, the power consumption of both compressors increases proportionally to the operating frequency. In addition, compared with the HT cycle, the LT compressor works at lower compression ratios. For the specific operating condition of $f_{LT} = 65$ Hz and $\Delta T_{SHLT} = 15$°C, the R134a/R744 system returns the compression ratio of 1.7:1 for the LT cycle and 4.1:1 for the HT cycle. The higher vapor density of R744 leads to less LT cycle power consumption, even with the compressor displacing a higher volume in the process. The R134a cycle demanded 2 kW, almost 33% less than the R438A HT. This trend persisted in all tests. It should be noted that, for a given ambient temperature, condensation pressure of R134a is lower than that of R438A thus contributing to a lower compression work.

Ten experimental results from Table 3 were chosen for the environmental impact calculation, Figure 10. Under the ordinate axis, air temperature and cooling capacity mean values are shown, for the same test conditions, for both refrigerant pairs.

Energy consumption is an important parameter to evaluate the indirect impact (TEWI INDIRECT) and,
consequently, the total TEWI. This fact can be observed by lower R134a/R744 TEWI values compared to the drop-in system. The R134a/R744 TEWI\textsubscript{INDIRECT} value is approximately 80% of that found for the R438A/R744 system, due to a higher energy consumption of the R438A compressor.

The use of a refrigerant with lower GWP reduces the direct impact, TEWI\textsubscript{DIRECT}. This fact is observed when comparing the TEWI\textsubscript{DIRECT} value for the cascade system with R438A (GWP of 2264) with the cascade system with R134a (GWP of 1430). The direct impact of the R134a/R744 system corresponds to 70% of the R438A/R744 system.

It is evident that the greater equivalent warming impact for the alternative R438A/R744 system is caused by the higher consumption of the HT cycle compressor and by the higher GWP of the same fluid, R438A.
7 | CONCLUSIONS

Contributing toward more sustainable and energy-efficient systems, this study compared the performance of a subcritical cascade system, originally designed for R134a/R744, with a second system where refrigerant R134a was replaced by R438A in a drop-in operation. The capability of this cascade system to work under variable thermal load conditions was demonstrated, with cooling capacities ranging from 4.58 ± 0.01 to 5.57 ± 0.02 kW. Such an operational flexibility also extended to the values established for the air temperature inside the cold room, as the lowest value reached −17.7°C and the highest, −2.9°C.

As far as cold-room temperature and cooling capacity are concerned, the drop-in R438A/R744 system performed well, in all tests, as results have shown that cold room air temperatures and cooling capacities, for base and drop-in cases, stayed within a range of 10% deviation, with either system reaching similar performances. The fact that R438 was designed to be used as a drop-in for R22 does not restrict its use solely for this application. The tests reported here show the technical feasibility of using R438 in conjunction with R744 to form a cascade refrigeration system, albeit with inferior energy and environmental results. Indeed, the R438A HT compressor presented the highest energy consumption in all tests. As a result that, COP values for the R438A/R744 pair were consistently (30%, approximately) below those of the original system with R134a/R744. Higher GWP and lower COP have thus contributed decisively to a greater environmental impact of the R438A choice. The total environmental impact, TEWI, for the R134a/R744 system was nearly 77% of the R438A/R744 pair, proving the alternative system to be not a good choice for an R134a/R744 drop-in, for environmental and performance reasons. A preliminary thermodynamic analysis would also reveal this drawback. Finally, the testing of a cascade refrigeration system with refrigerants R438A and R744 does not represent an endorsement or a promotion of its acceptance and use but simply an assessment of its energy and environmental performance.

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NOMENCLATURE

| Symbol | Definition |
|--------|------------|
| L      | annual rate of refrigerant replacement and leakage (%) |
| m      | refrigerant charge (kg) |
| ěm     | mass flow rate (kg/s) |
| N      | system operating life (years) |
| ODP    | ozone depletion potential (ref.: ODP R11 = 1) |
| P      | pressure (kPa) |
| Q      | cooling capacity (kW) |
| T      | temperature (°C) |
| TEWI   | total equivalent warming impact (kg CO₂ equivalent) |
| ěW     | rate of energy consumption (kW) |

GREEK SYMBOLS

| Symbol | Definition |
|--------|------------|
| /u1D6FC | recovery or recycling rate of refrigerant (%) |
| B      | indirect emission factor (kgCO₂/kWh) |
| Δ      | difference (—) |

SUBSCRIPTS

- ANNUAL: per year
- CD: condensation
- D: discharge
- DIRECT: direct effect on TEWI
- DC: compressor discharge
- EV: evaporation
- EVAP: evaporator
- I: inlet
- INDIRECT: indirect effect on TEWI
- LLT: liquid of the lower temperature cycle
- LV: liquid-vapor
- O: outlet
- REF: refrigerant
- SC: sub-cooling
- SH: superheating

ABBREVIATIONS

ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; CFC, chlorofluorocarbons; cond, condenser; EEV, electronic expansion valve; evap, evaporator; HCFC, hydrochlorofluorocarbons; HFC, hydrofluorocarbons; HT, high-temperature cycle; IPCC, Intergovernmental Panel on Climate Change; LLSLHX, Liquid-line suction-line heat exchanger; LT, low-temperature cycle; OR, open reciprocating; POE, polyol ester; SF, secondary fluid; SH, semi-hermetic; TXV, thermostatic expansion valve; VSC, variable speed compressor; VSSH, variable speed semi-hermetic.

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APPENDIX A

In Table A1 a few comparative tests were carried out with R22/R744. Although R22 is to be phased out worldwide, to protect the ozone layer, these results could be useful for plants still using R22, where a long-term replacement solution might be needed. Experimental apparatus and measuring methodology were the same as for R134a/R744 and R438A/R744 tests. One observes similar COP values between R438A and R22 systems.

| System | $f_{LT}$ | $\Delta T_{SH_{LT}}$ | $T_{LV_{LT}}$ | $T_{CD_{LT}}$ | $T_{L_{LT}}$ | $\dot{m}_{LT}$ | $\dot{W}_{LT}$ | $\dot{W}_{HT}$ | $P_{PV_{HT}}$ | $P_{CD_{HT}}$ | $T_{AIR}$ | $\dot{Q}_{SYS}$ | COP |
|--------|---------|-------------------|--------------|---------------|--------------|--------------|---------------|---------------|---------------|--------------|---------|----------------|-----|
| R22/   | 65.00   | 15                | −26.4        | −10.7         | 84.2         | −11          | 0.0189        | 0.625         | 2.85          | 3.4          | 12.4    | −8.4          | 5.43 | 1.5626        |
| R744   |         |                   |              |               |              |              |               |               |               |             |         |                |     |
|        | 10      | −25.9             | −10.4        | 82.3          | −11          | 0.0176       | 0.615         | 2.7           | 3.3           | 12.5        | −13.5   | 4.79          | 1.4449 |
|        | 5       | −25.4             | −10.1        | 80.4          | −10          | 0.0173       | 0.61          | 2.75          | 3.4           | 12.4        | −17.9   | 4.8           | 1.4286 |
|        | 60.00   | 15                | −26.5        | −10.6         | 79.8         | −11          | 0.0178        | 0.62          | 2.55          | 3.4         | 12.4    | −8.1          | 5.25  | 1.6562        |
|        | 10      | −25.7             | −10.4        | 77.1          | −10          | 0.0167       | 0.575         | 2.6           | 3.5           | 12.4        | −13     | 4.68          | 1.474 |
|        | 55.00   | 15                | −24.9        | −10.1         | 73.9         | −10          | 0.0179        | 0.535         | 2.45          | 3.4         | 12.5    | −4.9          | 5.05  | 1.6918        |
|        | 10      | −24.2             | −10.4        | 72.1          | −10          | 0.017        | 0.505         | 2.6           | 3.4           | 12.4        | −9.9    | 4.6           | 1.4815|
|        | 50.00   | 15                | −21.1        | −10.2         | 70.2         | −10          | 0.0162        | 0.445         | 2.55          | 3.3         | 12.7    | −3            | 4.53  | 1.5125        |