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Comparison of the impact of R449-A and R290 on refrigerated display cabinets using life-cycle climate performance method

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Abstract: Due to the high energy consumption of refrigerated display cabinets used in supermarkets, a life cycle cooling performance analysis to increase energy efficiency and reduce environmental impacts is the main subject of this study. It also emphasizes the need for cabinets that consume less energy and provide environmentally friendly working conditions. The Life Cycle Climate Performance (LCCP) of the two refrigerants R290 and R449-A was evaluated using measured data to compare the environmental impact of the refrigerants over the entire fluid and equipment life cycle, including energy consumption. Both vapor-compressed cooling cycles were thermodynamically modeled with the parameters taken from the experiments and the efficiency of system was calculated by using the EES software. The results show that the cabinet using R290 has lower compressor power utilization. The COP of the R290 system increased by 13% compared to the R449A system. The total daily energy consumption was also significantly lower for the R290 system. The energy efficiency index provides a standardized metric that can be used to compare the performance of different cooling systems. In this study, the energy efficiency index value was 17.3 points lower for the R290 system, indicating higher energy efficiency. The energy classes are "E" for the R449-A system and "C" for the R290 system, with the R290 system two classes higher in terms of energy class labeling. The EEI value of the system with R290 refrigerant has been reduced by 33% in comparison with the system with R449A refrigerant. The system using R290 refrigerant achieved a 33% reduction in energy consumption compared to the system using R449A refrigerant. The study also assessed the life cycle climate performance of the two systems. It was found that the R449-A system emits 19032.45 kg CO2e more over its lifetime compared to the R290 system. This was attributed to the relatively high global warming potential and energy consumption of R449-A refrigerant. However, when considering safety (flammability), it was concluded that R-449A has a lower environmental impact than R-290.

Keywords: LCCP; R449-A; R290; RDC.

1. Introduction

Commercial refrigerated display cabinets (RDCs) preserve and display food products by extending their shelf life. RDCs are in constant use 24 hours a day, and this continuous operation accounts for approximately 60% of the total energy consumption of supermarkets and food retail stores [1]. This energy-intensive situation in the commercial refrigeration system leads to the production of greenhouse gases (GHGs) with a global warming impact, directly based on the leakage of hydro-

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fluorocarbons (HFC) gases with high global warming potential (GWP) and indirect CO2 emissions from high electricity consumption [2]. The share of the refrigeration system in the total energy consumption is 15% and this is responsible for 1% of the CO_2 emissions in the world [3]. The increasing demand for fresh food with a growing population makes it inevitable that the consumption of electricity and the contribution of F-gases to global warming will increase many times over in the coming decades. Chlorofluorocarbons (CFCs) were banned by the Montreal Protocol (signed in 1987) and were replaced by hydrochlorofluorocarbons (HCFCs) and then by HFCs [4]. In contrast to CFCs, HFCs have a negligible ODP but a high GWP. Therefore, the contribution of HFCs to global warming is estimated to be in the range of 0.3°C to 0.5°C by 2100 [5]. According to Koronaki et al. [6] HFC's contribute significantly to the greenhouse effect, especially in large commercial refrigeration systems, where they leak around 11 per cent per year. Therefore, the revised F-Gas Regulation entered into force on 1 January 2015 to control fluorinated greenhouse gas emissions with zero ODP and low GWP. However, commercial refrigeration systems are still generally designed to use HFC refrigerants [7]. In recent years, hydrofluoroolefins (HFOs) synthetic refrigerants have been offered as an alternative 4th generation refrigerant to HFCs with low GWP (<1) and ODP (=0) value [8]. Also, hydrocarbon natural refrigerants are generally considered an alternative as they have thermodynamic properties with low GWP and zero ODP. R290 and R600a are generally accepted as alternative hydrocarbon natural refrigerants due to compatibility with current equipment and cooling installation in commercial refrigerators and freezers [9]. HC refrigerants and their mixtures are not only a good option with low GWP values for the environment but also show superior performance in terms of energy efficiency [10]. But hydrocarbon refrigerant charges have been limited for flammability concerns with safety precautions in commercial refrigeration systems [11]. The amount of hydrocarbon refrigerant in heat exchangers where the liquid phase is the majority in refrigeration systems is a key design consideration [12]. Therefore, the volume of heat exchanger must be decreased to improve the heat transfer coefficient (HTC) for lower coolant flow rate. In recent years, many researchers have investigated the use of microchannels to improve heat transfer in refrigeration systems using natural refrigerants [13-15]. Over the past few years, refrigeration manufacturers have focused on specialty blend gases that have low environmental impact, high energy and thermal performance, and low flammability risk. This is due to the flammability properties and the restrictions on the gas charge rate. HFC/HFO mixtures have been the preferred choice in vapor compression systems due to their higher efficiency and low GWP. Replacement of HFC/HFO/HC/R744 refrigerant blends with high GWP R134a, R404A and R410A refrigerants in terms of energy performance was evaluated by Aricapa et al. [7]. While R442A, R449-A and R407H stand out in terms of energy efficiency in conversion, R455A and R465A showed the maximum COP decrease. The use of the mixed gas refrigerant R449-A instead of the high GWP refrigerant R404A in supermarket RDCs was suggested by Mahnatch et al [16]. The mass percentages of R449-A refrigerant have been reported as 24.3%/24.7%/25.7%/25.3% because of blending R32/R125/R134a/R1234yf refrigerants. R449-A is a non-flammable and ODP-free refrigerant, according to Ghanbarpour et al. [17] Compared to R404A, which has a higher critical temperature and pressure than R449-A, the energy required for compression is reduced. In addition, the GWP of R449-A is approximately three times lower than that of R404A. Llopis et al. [18] predicted that lower GWP HFC/HFO mixture refrigerants (e.g. R448A, R449-A, R455A or R454C) as alternatives to R404A and R507 refrigerants could make the largest contribution to reducing emissions in commercial refrigeration by 2030.

Different techniques have been developed to evaluate the environmental impacts of refrigeration systems on global warming by leaking refrigerant and high energy consumption. Global warming potential (GWP) is a widely used measure of the greenhouse effect of refrigerants. The lower the GWP, the less the substance contributes to global warming [19]. GWP is the index used to compare the global warming effect of emitting a greenhouse gas with the effect of emitting a similar amount of CO_2, which is estimated over a given time horizon. An indicator called Total Equivalent Warming Impact (TEWI) is used to assess the environmental impact of systems or processes that use energy, in addition to the direct impact of the refrigerant [20]. For low GWP refrigerants, the direct effect is quite small compared to the indirect effect. Therefore, the performance of energy consumption data based on TEWI will greatly influence the outcome of a refrigerant comparison [21]. The TEWI metric, unlike the GWP, is an indicator that includes emissions associated with energy production but does not include all relevant indirect emissions associated with the refrigerant life cycle, such as emissions associated with transport and production of the system and refrigerant. An approach that holistically evaluates the environmental impact of different refrigerants and assesses lifecycle climate performance together with environmental impact is LCCP. This tool is used to evaluate the GWP effects of the analyzed refrigerating system in terms of direct and indirect carbon emissions as total CO2eq throughout the entire life cycle [22]. A standardized approach to the use of LCCP and comprehensible data sources for all aspects of the calculation is proposed by Troch et al [23]. It was recommended that the data sources be used for the calculation of averages of all LCCP inputs. An open source and modular solution for LCCP based analysis of vapour compression refrigeration systems was presented by Beshr et al. [24] evaluated the refrigeration systems of a supermarket using low GWP refrigerants using a method based on LCCPs. It was found that the use of low GWP refrigerants resulted in a significant reduction in the impact on the uncertainty of the total emissions of the system, with a reduction in the direct emission value. The most environmentally friendly refrigerants were identified as R1270, R290 and R152a in the LCCP assessment, which evaluates the entire life of the refrigerant with a holistic approach that measures its impact on system emissions. Another LCCP-based analysis was carried out by Lee et al. [25] for different vapor compression cycles (VCC) using low GWP refrigerants. With the R290 refrigerant, they observed a significant reduction in the LCCP value of about 15.1%. In heat pump applications using R290 refrigerant, total CO_2 emissions were reduced by approximately 22.3%. A LCCP-based model of refrigeration and heating systems has been investigated by Choi et al. [26] in South Korean weather conditions. The LCCP-based assessment method was reviewed and applications for identifying refrigerants to replace high GWP refrigerants were documented by Wan et al. [27]. Using the developed LCCP method, Choi et al. [28] investigated the environmental impact of household refrigerators. The results showed that system performance and manufacturing emissions are the dominant factors influencing lifecycle emissions. They found that by selecting aluminum material in the condenser in a well-insulated refrigeration system with the binary cycle option, CO_2 emissions can be reduced by up to 25%. Li et. al. [29] focused on food transport refrigeration systems and conducted a life cycle climate performance study. They found that replacing R404A refrigerant with R452A, which has a lower global warming potential, could reduce emissions in the food transport refrigeration system by 5-15%. They also found that reducing the ambient temperature from 32°C to 15.5°C could reduce emissions by up to 60% for fresh produce and up to 39% for frozen produce. In addition, the study highlighted that reducing the refrigerant leakage rate from 25% to 10% could result in emissions reductions of 13% for fresh products and 4% for frozen products. Regulations are constantly being updated to reduce the use of high GWP refrigerants, promote the use of refrigerants with a lower environmental footprint, increase the energy efficiency and performance of cooling systems and ensure the implementation of eco-design requirements throughout the lifecycle of cooling equipment [30]. Eco-design has become a key issue in the development of refrigeration systems with the adoption of EU Regulation 2019/2019 and EU Regulation 2016/2281, which set eco-design requirements and frameworks for energy-related products, including refrigeration systems, to achieve low lifetime emissions and low energy consumption targets for both commercial and domestic applications [31]. To comply with these regulations and meet the new technological challenges, research and development efforts are required to identify innovative solutions that ensure high performance, low energy consumption, and the use of alternative fluids with limited environmental impact. This includes considering all life cycle phases, not just the use phase, in the design and development of refrigeration systems. In the literature review, there are many studies on LCCP assessment methodologies. However, the life cycle emission assessments of RDC systems are limited in scope. In this study, an experimental environmental assessment was carried out on the energy consumption and refrigerant-related emissions of RDCs. The environmental impacts of the refrigerants R449-A and R290 were compared using LCCP. In addition, an energy label classification was performed for RDCs using two different refrigerants. An analysis of the lifecycle climate performance of commercial RDCs and information on the reduction of CO_2 emissions over a 10-year operating life because of this performance analysis is presented in this study.

2. Materials and Methods

2.1. LCCP Calculation

LCCP is a calculation methodology developed to determine the lifecycle environmental impact of refrigeration and air conditioning systems operating with a stationary vapor compression cycle powered by the local electrical grid. LCCP calculations are made in units of CO_{2e} or CO_{2eq}/kWh, consisting of direct emissions (refrigerant leaks) and indirect emissions (energy consumption for manufacturing). LCCP concept is illustrated in ▶**Figure 1**. Direct emissions are affected by refrigerant emissions and atmospheric degradation, while indirect emissions are affected by energy consumption, emissions from production, material, and refrigerant recycling.

LCCP, which consists of two emission values, can be calculated as in Eq. (1).

$$\text{LCCP}=\text{Direct Emissions}+\text{Indirect Emissions} \tag{1}$$

Annual leaks, catastrophic leaks and leaks resulting from disposal of the unit constitute the direct emission value throughout refrigeration's life cycle. Direct Emissions (DE) account for the refrigerant leakage over the course of the lifetime of unit and calculated by the following [32]:

$$\text{Direct Emissions}=C\times(L\times ALR+EOL)\times(GWP+Adp.GWP) \tag{2}$$

Here, the charge amount of the refrigerant is C (kg); L is an average lifetime of component (year); ALR is the annual leak rate (%); EOL is the end-of-life refrigerant leakage (%); GWP is Global Warming Potential (kgCO_{2e}/kg); Adp.GWP is the atmospheric degradation product of the refrigerant (kgCO_{2e}/kg) GWP.

Indirect emissions contain emissions due to energy consumption in operation, manufacturing emissions

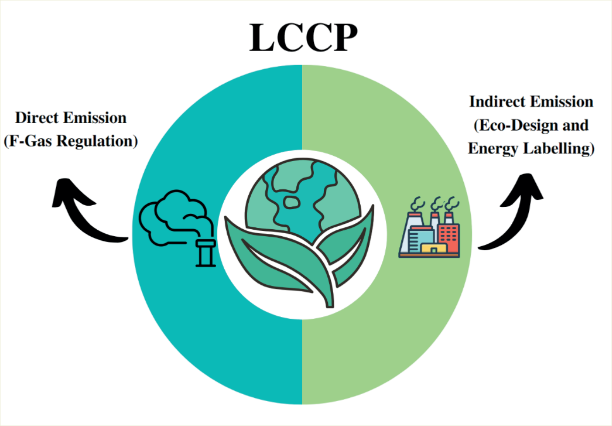

Figure 1. LCCP graphical representation

and emissions from unit disposal. Indirect emissions are consisted of the use of the unit over its lifetime and account for the following [32]:

$$\begin{aligned} \text{Indirect Emissions} = {} & L \times AEC \times EM \\ & + \sum (m \times MP) \\ & + \sum (MR \times RM) \\ & + C \times (1 + L \times ALR) \times RFM \\ & + C \times (1 - EOL) \times RFD \end{aligned} \tag{3}$$

AEC is Annual Energy Consumption (kWh); EM is the electricity generation emission ($kgCO_{2e}/kWh$); m is the mass of RDC (kg); MP is the material production emission ($kgCO_{2e}/kg$); MR is the mass of recycled material (kg); RM is the recycled material ($kgCO_{2e}/kg$); RFM is the refrigerant manufacturing emissions ($kgCO_{2e}/kg$); RFD is the refrigerant disposal emissions in ($kgCO_{2e}/kg$). Values of parameters were taken based on the guideline for LCCPM[32]. Mechanical vapor compression system is used in refrigerated display cabinets. Approximately 80-95% of the LCCP emissions of the mechanical vapor compression systems used consist of indirect emissions. The GWP values of the refrigerants analyzed in the experiment are given in ▶**Table 1**. The ODP and GWP values of the refrigerants R449-A and R290 are shown in ▶**Table 1**. The R290 refrigerant is more environmentally friendly than R449-A based on these values.

Table 1. GWP values for refrigerants

Refrigerant	Class	ODP	GWP	Adp.GWP
R449-A	A1	0	1397	-
R290	A3	0	3	-

Emissions from material production have been calculated considering the International Refrigeration Institute (IIR) standard. In addition, production emission values of these materials are given in IIR standard (released 2015)[32]. CO_2 emission values per unit area, expressed in [$kgCO_{2e}/m2$], can be calculated using the average coefficient per electricity consumption (ACPEC) as follow:

$$CO_2\, emission = \frac{ACPEC \times TEC}{TDA} \tag{4}$$

2.2. Experimental analysis

In this study, two different low GWP refrigerants R449-A and R290 were analyzed in commercial open-type RDCs designed with the same VCC system. Total display area (TDA) of RDC is 4.3m^2 and there are 5-piece shelves and a pan at the bottom of the cabinet designed seen in ▶**Figure 2**. Experiments were conducted under EN ISO 23953-2:2015 (298.15K, 60% relative humidity) test room conditions. The mixed refrigerant R449-A was used in the first experimental cooling cycle while R290 natural refrigerant was used as the second refrigeration circuit. The designed systems were tested under 0.1-0.2m/s airflow velocity conditions for 24 hours. During the test activities, M-Pack temperatures, temperature, and pressure values of the refrigeration system equipment (compressor, condenser, and evaporator), energy consumptions of compressor and other components were measured from certain points. The test room measurement instruments are specified in ▶**Table 2** as part of the EN ISO 23953-2:2015 standard. The prototype of the open type RDC is given in ▶**Figure**

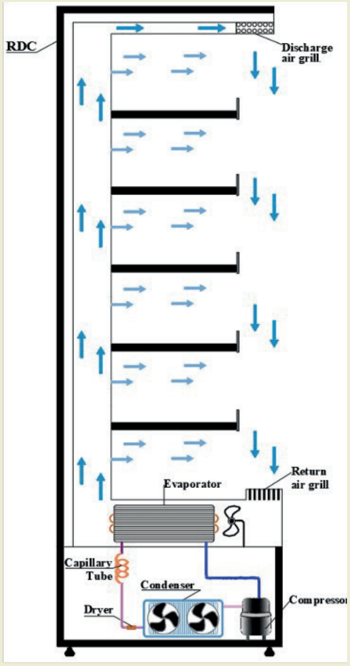

Figure 2. Schematic of ORDC

3. RDC systems were designed to operate with R449-A refrigerant and R290 refrigerant. Both mechanical vapor compression refrigeration cycles consist of two compressors, two condensers, two capillary tubes and an evaporator with five fans given in **▶Figure 4**. While 1400g(2x700 g) of R449-A refrigerant was charged to the cooling system, this amount was 300g(2x150 g) for R290. The experimental conditions were set at a condenser temperature of 45°C and an evaporator temperature of -10°C, which are close to the practical operating conditions. The climate class of the test room is 3, the dry bulb temperature is 298.15K±1K, the relative humidity is 60±5%, and the air velocity varies between 0.1-0.2 m/s. EKM (electro-commutated) type condenser and evaporator fan, piston hermetic type compressor, microchannel condenser and copper tube aluminum fin evaporator were used in the Refrigerated Display Cabinet.

Table 2. Specifications of measurement instruments

Measuring device	Measuring range	Accuracy
Refrigerant flow meter	0–1000kg/h	±0.1%
Energy meter	0–16 A	±0.2%
T-type thermocouple	233.15–473.15 K	±0.1%
Thermohygrometer	0–100%RH 273.15–312.15 K	±1.5% ±0.03%
Digital manifold gauge	223.15–423.15 K 1– 0 bar	±0.1% ±0.01%
Anemometer	0–2 m/s	±0.01%
Low-pressure transmitter	0.5–8 bar	±0.01%
High-pressure transmitter	0–30 bar	±0.1%

The probes measuring the refrigerant temperatures input and output the evaporator, the refrigerant temperatures entering and leaving the condenser, the low and high pressures of the refrigerant input and output the compressor, the measurement of the air temperatures entering the air-on grille of the refrigerant and output the air-off honeycomb, the energy consumption of the refrigerant, the refrigerant flow measurement tests are carried out. The properties and precisions of the measurement instruments are given in **▶Table 2**.

The data obtained because of the experiments were found using measuring devices in accordance with the standard. Uncertainty analysis is important to find the uncertainty of measurement and to make precise measurement. They are errors caused by test conditions, measuring devices, ambient conditions, reading and measuring points. For this reason, uncertainty analysis is important in finding accurate results by reaching the desired experimental standards. The total uncertainty is calculated with the Equation 5-6.

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (5)$$

$$wn = \sqrt{(A_1)^2 + (A_2)^2 + \cdots + (B_n)^2} \quad (6)$$

Where n is the number of parameters, Wn is measured uncertainty of each parameter, WR is total uncertainty, wn denotes the uncertainty of each independent parameter (A and B) measured.

Figure 3. The prototype of ORDC and M-packages

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2.3. Theoretical Analysis

RDCs run with mechanical vapor compression refrigeration cycle. A schematic diagram is illustrated in ▶**Figure 4**. Energy conservation equation is utilized to calculate the total energy consumption in Eq.7.

$$E_T = E_{fans}t_{fans} + E_{compressor}t_{compressor} + E_{defrost}t_{defrost} + E_{other}t_{other} \tag{7}$$

The power consumption of the compressor is calculated as:

$$\dot{W}_c = \dot{m}\left(h_2 - h_1\right) \tag{8}$$

Where, h_1 is the enthalpy of the compressor input and h_2 is the enthalpy of the compressor output.

The capacity of evaporator is:

$$\dot{Q}e = \dot{m}\left(h_1 - h_4\right) \tag{9}$$

Here, h_4 is evaporator inlet enthalpy and h_1 is evaporator outlet enthalpy.

The COP of the RDC system is calculated by combining the refrigeration loads and power of compressor as below:

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp}} \tag{10}$$

The energy efficiency index (EEI) value can be calculated with European Union regulation of (EU) 2017/1369:

$$EEI = \frac{AE}{SAE} \tag{11}$$

Annual energy consumption, expressed in kW/h, can be calculated as follows:

$$AE = 365 \times E_{daily} \tag{12}$$

Edaily is energy consumption of the RDC over 24 hours, expressed in kWh/24h.

$$E_{daily} = \left[\left(\dot{W}_{comp}t_{comp}\right) + \left(\dot{W}_{ef}t_{ef}\right) + \left(\dot{W}_{cf}t_{cf}\right) + \left(\dot{W}_{h}t_{h}\right) + \left(\dot{W}_{l}t_{l}\right)\right] \tag{13}$$

SAE as a reference value can be calculated as below:

$$SAE = (M + N \times Y) \times 365 \times C \times P \tag{14}$$

The values of M, N, P and C are given in ▶**Table 3**. These parameters are specified with (EU)2017/1369 regulation for M1 temperature class experiment condition in vertical combined supermarket refrigerator cabinets. Y, expresses in m^2, is the sum of the total display area.

3. Results and Discussions

This study evaluated the R449-A and R290 refrigerants energy efficiency and environmental performance in the same designed RDC system. Both low GWP refrigerants were compared with thermodynamically and LCCP analysis methods in accordance with EN ISO 23953-2:2015 standard under M1 medium temperature test conditions. M1 package temperature class and test room climate class 3, as described in ISO 23953-2, for a 10-year service life in an open commercial refrigeration display cabinet. This choice is consistent with previous studies on the same scope [33-35]. Theoret-

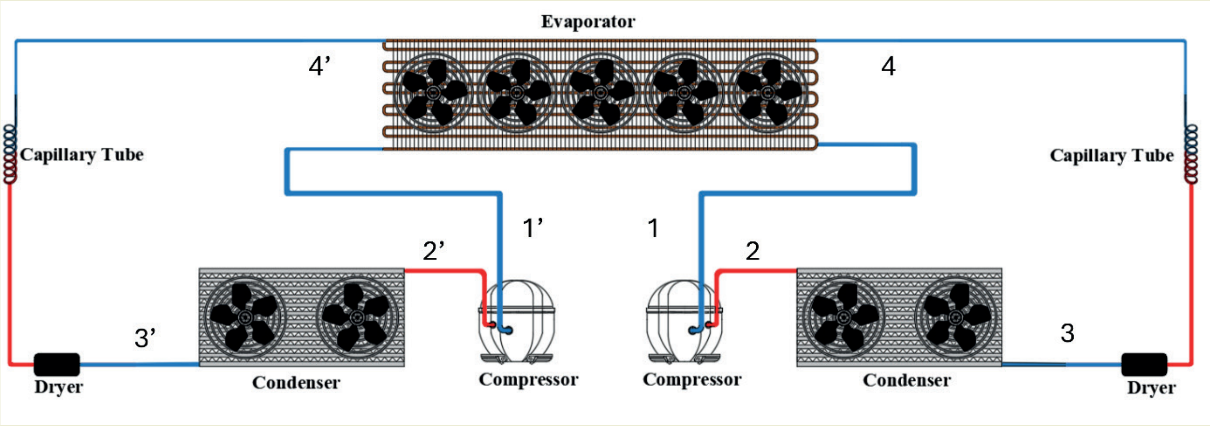

Figure 4. Schematic of the mechanical vapor compression refrigeration system

Table 3. M1 Temperature class vertical RDC coefficient values

Coefficient	Value
M	9.1
N	9.1
P	1.1
C	1.15

ical and experimental results were presented in this section. The evaporator inlet temperature (EIT) and evaporator outlet temperature (EOT) values for open-type RDCs used R449-A and R290 refrigerants. Open-type RDCs according to EN ISO 23953-2:2015 within the test period, firstly 12h switched on lighting, without the night-covers secondly 12h with the night-covers and the cabinet lighting switched off. The total uncertainty value was calculated as 2.3312% Therefore, this value is at an acceptable level and the measurements made in the study can be considered reliable. The low-temperature source value was T_L=263.15K and the high-temperature value was T_H=318.15K during the experiment. Carnot coefficient of performance value was determined as $\mathbf{COP_{carnot} = 4.8}$. Moreover, the compressor power of the RDC system for R449-A and R290 refrigerants were recorded as $\mathbf{\dot{W}_{comp} = 1640W}$ and $\mathbf{\dot{W}_{comp} = 1448W}$, respectively. Due to several factors, including the more efficient thermodynamic properties of the R290 refrigerant, compressor run time and power consumption were lower than expected [36]. The reduction in the time required for the delivery of cooled air further reduces energy consumption and the overall energy efficiency index. The cooling capacity was $\mathbf{\dot{Q}_e} = \mathbf{3145}\,\mathrm{W}$ for refrigerant RDC systems. COP value was 1.92 for R449-A refrigerant while it was 2.17 for low GWP natural refrigerant R290. The COP value of the system operating with R290 was obtained as 11.5% higher than R449-A refrigerant used system. As a result of lower compressor power requirements in the same cooling process, the COP has been significantly improved when R290 is used. Furthermore, the second law efficiencies of R449-A and R290 were calculated as 40% and 45.2%, respectively. Because of the same reason as in the COP calculations, the second law efficiency of the R290 system is improved by 5.2% as compared to R449-A system. The inlet and outlet temperatures of the evaporator are given in ▶**Figure 5**, for both refrigerants R449-A and R290. The difference between the inlet and outlet temperatures of R290 used case is less than in the case used R449-A refrigerant. Evaporator inlet and outlet temperatures differed by 4°, and a 3% increase was measured with R449-A refrigerant. The difference between the evaporator inlet and outlet temperatures decreases at night when the covers are closed. The evaporator inlet temperature is about 1 degree less where R449-A refrigerant was used in night period. Daily energy consumption in the R449-A refrigerant case was 31.55kW/day, while in the R290 case, it was 21kW/day. This illustrates the impact of the reduced compressor on cycle time savings [36]. In this case, daily energy saving was 10.55kW/day. Similarly, annual consumptions (AE) were 11515.75kW/year and

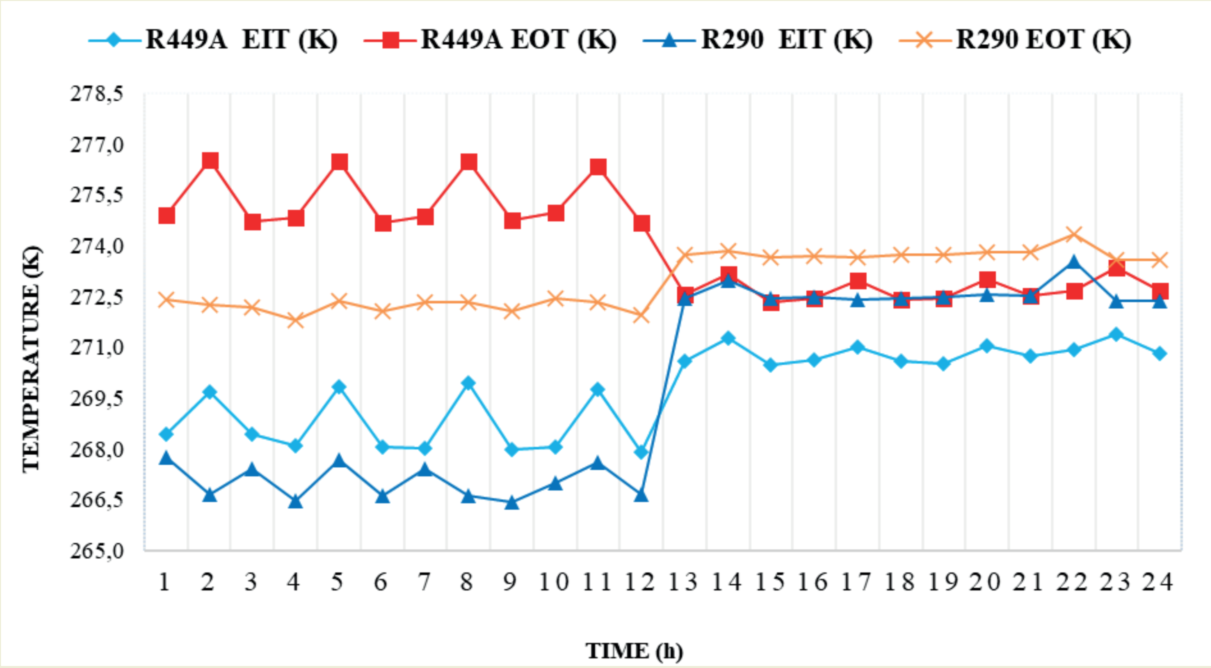

Figure 5. Evaporator inlet-outlet temperature graph

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7665kWh/year for R449-A and R290 refrigerant systems, respectively. In this way, annual energy saving was calculated as 3850.75 kWh/year. The SAE value of the experimental setup was calculated as 22269kWh/year for all compartments with the same temperature class commercial refrigerator.

The temperature of the refrigerant input and output of the condenser is given in ▶**Figure 6**. When the R449-A refrigerant enters and exits the condenser compared with the R290 refrigerant, there is a difference in temperatures. While the condenser inlet temperature drop was measured at 6%, the outlet temperature difference was measured at 2%. One of the most important reasons for this difference is the use of R290, a natural refrigerant with low ODP and GWP values and high heat transfer potential. LCCP evaluation of the two refrigerant systems was also performed in this study and the results were summarized.

The summary of the evaluations is presented in ▶**Figure 7**. In addition, the emission values obtained from the LCCP analysis are given in ▶**Table 4**. The total lifetime CO_2 emission in the R449-A system was determined as 61853.93 $kgCO_{2e}$ and the total lifetime CO_2 emission in the case of R290 was determined as 42821.48 $kgCO_{2e}$. Therefore, the use of R449-A as the refrigerant results in 19032.45 kg CO_{2e} more emissions to the environment over the lifetime of the system.

The excess CO_2 emissions observed in the R449-A system come mainly from both direct and indirect emissions. In the direct emissions, due to the annual refrigerant leakage and end-of-life (EOL) refrigerant leakage, the total emission was calculated as 3716.02 $kgCO_{2e}$ for the R449-A system. 3520.44 $kgCO_{2e}$ of this value comes from the annual refrigerant leakage, whereas annual refrigerant leakage emission was calculated as 1.71 $kgCO_{2e}$ in the R290 system. Due to the high GWP value of R449-A, the direct emission values were higher compared to the R290 system. Nevertheless, the major difference between the two cases comes from indirect emission, 61852.22 $kgCO_{2e}$ in total was estimated in the R449-A system and 42819.77 $kgCO_{2e}$ in total was estimated for the R290 system. The difference between the two systems in the indirect emissions is due to the high annual energy consumption observed in the R449-A system. Since the equipment is the same for both systems, emissions due to equipment manufacturing and equipment EOL are the same for this type of RDC. Due to unavailable refrigerant manufacturing emission data for R449-A, the emission due to refrigerant manufacturing for R449-A was neglected, whereas this value was calculated as 0.04 $kgCO_{2e}$ for the R290 system. EEI values were calculated as 51.7 for R449-A refrigerant system and 34.4 for R290 refrigerant system consequently. By evaluating the EEI, RDCs can be identified the energy-efficient features. According to the EEI value of 51.7 the energy class "E" was found for R449-A refrigerant system whereas R290 system was in the energy class of "C" with 34.4 EEI value. Energy efficiency can be significantly improved when R290 is used as the refrigerant. When these rates are considered, the system using R290 refrigerant has 11.5% higher COP value, 33% lower energy consumption, 33 % lower EEI value compared to the system using R449-A refrigerant, in this case, the energy label class is higher in higher levels.

The emission values obtained from the LCCP analysis are given in ▶**Table 4**. The total lifetime CO_2 emission in the R449A system was determined as 61853.93 $kgCO_{2e}$ and the total lifetime CO_2 emission in the case of R290 was determined as 42821.48 $kgCO_{2e.}$ Therefore, the use of R449A as the refrigerant results in 19032.45 kg CO_{2e} more emissions to the environment over the lifetime of

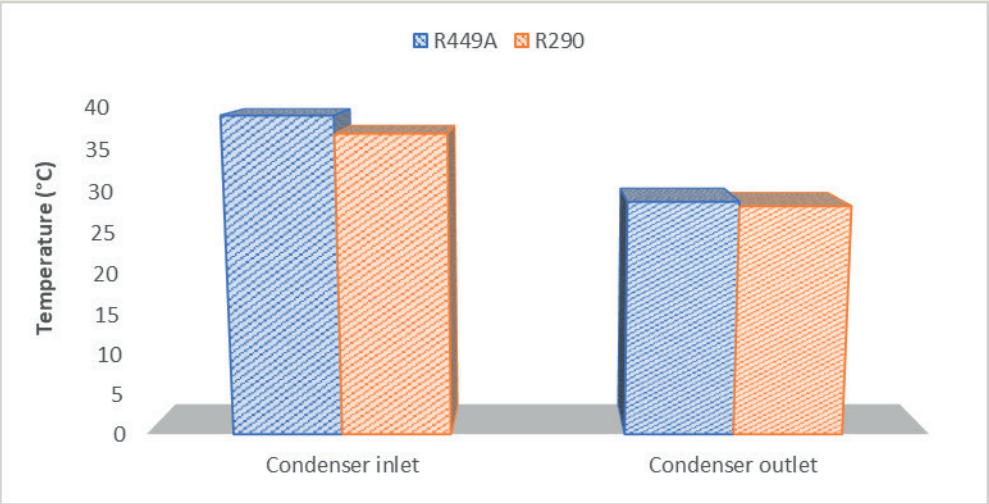


Figure 6. Condenser inlet and outlet temperature graph

Table 4. LCCP results of R449-A and R290 systems

LCCP Results	R449-A	R290
Total Lifetime Emission (kgCO$_{2e}$)	61853.93	42821.48
Total DE (kgCO$_{2e}$)	3716.02	1.71
Annual Refrigerant Leakage (kgCO$_{2e}$)	3520.44	1.62
EOL Refrigerant Leakage (kgCO$_{2e}$)	195.58	0.09
Adp. GWP (kgCO$_{2e}$)	-	-
Total IE (kgCO$_{2e}$)	61852.22	42819.77
Equipment Mfg (kgCO$_{2e}$)	1599.30	1599.30
Equipment EOL (kgCO$_{2e}$)	25.29	25.29
Refrigerant Mfg (kgCO$_{2e}$)	-	0.04
CO$_2$ emission per m2(kg CO$_{2e}$/m^2)	3.28	2.18

the system. These results come from the total energy consumption of 11515.75kWh/year and 7.665kWh/year for R449-A and R290, respectively. Transcribing the energy consumption to the total life of 10 years of the RDCs, LCCP evaluation indicates that an additional 19032.49 kgCO$_{2e}$ will be released to the atmosphere in the case of R449-A.

4. Conclusions

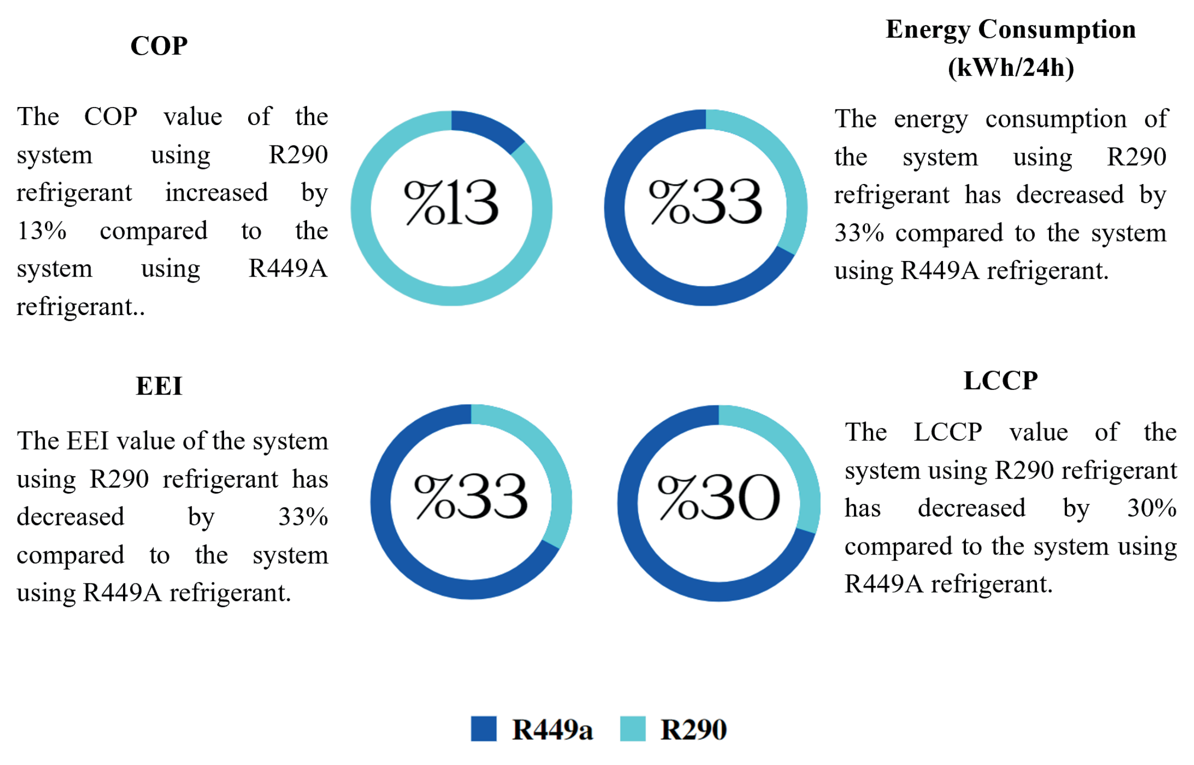
Theoretical and experimental analyses of an open RDC system with two working refrigerants (R449-A and R290) were performed in this study. An environmental impact assessment was performed by calculating EEI and using the LCCP method based on energy consumption measurements. Analysis results are presented below:

- With the use of R290 refrigerant, a reduction in compressor power of approximately 200W can contribute to energy efficiency by providing a significant reduction in electricity consumption. Thus, the lower energy consumed in the compression process enabled the performance of RDC with R290 refrigerant to be 11.5% higher.

- It was determined that the annual energy consumption of the R290 system for the same cooling area was 3850.75kWh/year lower than the R449-A system.

- It was possible to reduce the amount of daily CO$_2$ emissions related to RDCs' daily energy consumption thanks to the use of R290 refrigerant.

- With R449-A refrigerant, the EEI value was increased from 34.4 to 51.7. As a result, the energy



The COP value of the system using R290 refrigerant increased by 13% compared to the system using R449A refrigerant..

The energy consumption of the system using R290 refrigerant has decreased by 33% compared to the system using R449A refrigerant.

The EEI value of the system using R290 refrigerant has decreased by 33% compared to the system using R449A refrigerant.

The LCCP value of the system using R290 refrigerant has decreased by 30% compared to the system using R449A refrigerant.

Figure 7. COP, EEI, energy consumption, LCCP rates

class of RDC in the same area using R449-A refrigerant was E, while the C energy class was determined for R290. Due to the considerably less energy consumption by R290 working refrigerant, the energy class of the system was two classes higher.

- LCCP evaluation of both systems was performed. Quantitatively, the main difference comes from both direct and indirect emissions. Due to the high GWP value of R449-A, the direct emission for the R449-A system was calculated as 3716.02 $kgCO_{2e}$, while this value was only 1.71 $kgCO_{2e}$ in the R290 system. In indirect emission results, the main and almost only difference comes from the annual energy consumption.
- The results show that the R449-A system releases 30% more kg CO_{2e} into the environment over the lifetime of the system.
- Due to high energy consumption of R449-A, emissions were 61852.22 $kgCO_{2e}$ whereas indirect emission of R290 system was calculated as 42819.77 $kgCO_{2e}$.
- The system using R290 refrigerant used 78% less refrigerant compared to the system using R449-A refrigerant.
- The system using R290 refrigerant shows superior performance compared to the system using R449A refrigerant, with a 13% increase in COP, a 33% reduction in EEI and energy consumption, and a 30% reduction in LCCP.
- Thanks to the new generation refrigerant with zero ODP and low GWP, the impact of RDCs on global warming can be reduced.

As a result of the calculation of indirect emissions and direct emissions, it has been observed that indirect emissions are higher. In indirect emissions, it is foreseen that it will be beneficial to reduce the effect of emissions released to nature due to the energy used to produce the refrigerant. It can also be proposed to reduce the energy consumed for the production, assembly, and transport of systems/components, as well as to reduce emissions from the energy consumption required for the recovery of the refrigerant/system.

Future studies will use a machine learning model to develop sustainable design and manufacturing processes for energy-intensive commercial refrigeration. This approach will address the challenges of the experimental investigation of different conditions in the field and in test chambers, which are often costly and time consuming. Our aim is to streamline these processes, making them more efficient and effective by machine learning.

Nomenclature

ACPEC	Average coefficient per electricity consumption
RDC	Refrigerated Display Cabinet
GWP	Global Warming Potential
GWPadp	Adaptive Global Warming Potential
CFD	Computational Fluid Dynamics
DAG	Discharge Air Grille
DE	Direct Emissions
IE	Indirect Emissions
RAG	Return Air Grille
COP	Coefficient of Performance
EEI	Energy Efficiency Index
AE	Annual Energy Consumption Amount
SAE	Reference Value of the Annual Energy Consumption Amount
LCCP	Life Cycle Climate Performance
EOL	End of Life
ODP	Ozone Depletion Potential
TDA	Total Display Area
TEC	Total Energy Consumption (kWh)
E	Energy (kWh)
Q	Rate of Heat Transfer (kW)
W	Power (kW)
T	Temperature (K)
η	Second Law Efficiency (%)
mr	Mass of Refrigerant (kg)

Subscripts

max	maximum
comp	compressor
T	total
def	defrost
e	evaporator
r	refrigerant

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Research Ethics

Ethical approval not required.

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