Düzce University Journal of Science & Technology, 11 (2023) 2293-2308

Düzce University
Journal of Science & Technology

Research Article

The Analysis of Next-Generation Refrigerants in Terms of Energy, Exergy, and LCCP Perspective

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DOI: 10.29130/dubited.1388565

ABSTRACT

In this study, commonly used hydrofluorocarbon (HFC)-based refrigerants R404A and R410A, as well as hydrofluoroolefin (HFO)-based environmentally friendly next-generation refrigerant R1234yf with a low global warming potential (GWP), were analyzed in terms of energy, exergy, and life cycle climate performance (LCCP) in refrigeration and air conditioning systems. All three refrigerants were examined at four different evaporation temperatures (-30°C, -15°C, -5°C, 0°C) with a constant condenser temperature of 50°C using a simulation program. For different evaporation temperatures, the performance of the refrigerants was evaluated using the first and second laws of thermodynamics, and performance coefficients, exergy efficiency, and exergy destruction were calculated. Additionally, the amount of kgCO_2e equivalent was calculated using the LCCP method. In the study, it was found that the compressor energy consumption of R410A and R1234yf refrigerants was similar and approximately 7% lower than that of the R404A refrigerant. The highest coefficient of performance (COP) value was determined for R1234yf. It was observed that R1234yf refrigerant had the highest exergy efficiency starting from -15°C. The kgCO_2e equivalent emission values calculated using the LCCP method revealed that R404A had the highest CO_2 emissions, while R1234yf had the lowest. Furthermore, based on the simulation study and theoretical calculations, it was determined that R410A and R1234yf refrigerants could be considered as alternative choices to R404A refrigerants in systems where two refrigerants are used.

Keywords: *Energy, Exergy, GWP, LCCP, Refrigerant*

Yeni Nesil Soğutucu Akışkanların Enerji, Ekserji ve LCCP Perspektifinde Analizi

Öz

Bu çalışmada, soğutma ve iklimlendirme sistemlerinde yaygın olarak kullanılan hidroflorokarbon (HFC) tabanlı R404A, R410A akışkanları ile hidrofloroolefein (HFO) tabanlı düşük küresel ısınma potansiyel oranına sahip ve ozon tabasına dost yeni nesil soğutucu akışkan olan R1234yf enerji, ekserji ve yaşam döngüsü iklim performansı (LCCP) açısından incelenmiştir. Her üç soğutucu akışkan dört farklı buharlaşma sıcaklığı (-30°C, -15°C, -5°C, 0°C) ile sabit kondenser sıcaklığında (50°C) simülasyon programı kullanılarak gerçekleştirilmiştir. Farklı buharlaşma sıcaklıkları için, soğutucu akışkanların performansları termodinamiğin birinci ve ikinci kanunu kullanılarak değerlendirilmiş ve sistemlere ait performans katsayıları, ekserji verimi, ekserji yıkımı hesaplanmış, LCCP yöntemiyle de kgCO_2eşd. miktarı hesaplanmıştır. Çalışmanın sonunda R410A ve R1234yf soğutucu akışkanlarının kompresör enerji tüketimlerinin birbirine yakın ve R404A soğutucu akışkanına göre yaklaşık %7 daha düşük olduğu tespit edilirken en yüksek COP değeri R1234yf olarak belirlenmiştir. R1234yf soğutucu

[1]11. Uluslararası Meslek Yüksekokulları Sempozyumu'nda (UMYOS) sunulmuştur.
Received: 09/11/2023, Revised: 25/11/2023, Accepted: 09/12/2023

akışkanın -15°C'den itibaren en yüksek ekserji verimine sahip olduğu görülmüştür. LCCP yöntemi ile hesaplanan $kgCO_2$eşd. emisyon değerlerinde CO_2 emisyonu yüksek olan soğutucu akışkanın R404A, en düşüğün ise R1234yf olduğu tespit edilmiştir. Ayrıca yapılan simülasyon çalışması ve teorik hesaplamalar sonucunda ele alınan soğutucu akışkanlardan R404A soğutucu akışkanı yerine R410A ve R1234yf soğutucu akışkanlarının kullanılması iki soğutucu akışkanın kullanıldığı sistemlerde alternatif olarak kullanılabilir olduğu tespit edilmiştir.

Anahtar Kelimeler: *Enerji, Ekserji, GWP, LCCP, Soğutucu Akışkan*

I. INTRODUCTION

Reducing greenhouse gas emissions from energy consumption is a key objective in combating climate change and promoting environmental sustainability. One effective approach is using renewable energy sources and high-efficiency technologies instead of conventional energy sources. However, more than these measures are required. In this context, the energy consumption and environmental impact of refrigeration and air conditioning systems operating on vapor compression refrigeration cycles have emerged as significant concerns. Conventional refrigerants, such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), have been recognized for their adverse effects on the environment because of their global warming potential and, ozone-depleting potential (ODP). To mitigate the adverse environmental impacts of refrigerants, various laws, and regulations, including the Montreal Protocol, the Kyoto Protocol, and the Paris Agreement, have been enacted. Therefore, alternative, or next-generation refrigerants for vapor compression systems have become a critical issue. With technological advances, a wide array of cooling systems has been developed to enhance climate control and cooling solutions by incorporating eco-friendly next-generation refrigerants. These include hydrofluoroolefins (HFOs) and hydrocarbons (HCs), which help reduce the negative environmental impacts, fostering more sustainable and environmentally friendly cooling technologies.

Key criteria for next-generation refrigerants include a low ozone depletion potential, low global warming potential (GWP), high efficiency, and safety in usage [1]. To minimize energy consumption and greenhouse gas emissions, there is a need for environmentally friendly refrigerants with low GWP and zero ODP.

Numerous studies have been conducted on production and performance assessment of next-generation and alternative refrigerants. When reviewing these studies, one conducted by Berk stands out. In Berk's study, a 2.05 kW cooling capacity air conditioner operating with R22 refrigerant was compared to using R422A and R424A refrigerants. Experimental research focused on energy parameters, particularly cooling capacity, and coefficient of performance (COP). The experiments were carried out using an outdoor duct, an insulated room, a condenser, and an indoor split air conditioning unit that maintained a constant outdoor temperature. The study concluded that using R422A and R424A refrigerants in place of R22 resulted in lower COP values compared to the system using R22. However, it was noted that the temperature conditions simulated in this study, representing various climate conditions, could be beneficial for air conditioning. Therefore, the study recommended using R422A or R424A instead of R22 in hot climate regions. [2]

Kılıç and Arabacı conducted an energy analysis on the use of LPG (R1270 propylene) as a refrigerant in a vapor compression refrigeration system. They employed the Coolpack program to perform calculations and investigate the effects of LPG (R1270-Propylene) on the system's performance under various operating conditions. Findings revealed that an increase in the evaporator temperature enhanced the COP. Conversely, when the condenser temperature increased, the COP value decreased. It achieved the highest COP value under operating conditions with a 25°C condenser and a -1°C evaporator temperature. This study highlights the impact of temperature variations on the system's performance. The potential advantages of using R1270 propylene as a refrigerant in vapor compression refrigeration systems are shown [3].

In another study, Yıldız and Yıldırım conducted a theoretical analysis was carried out to examine the performance of refrigerants R134A and R513A. It also evaluated the environmental impact of the used refrigerants through a Life Cycle Climate Performance (LCCP) analysis. The energy performance of refrigerants was assessed at different evaporator and condenser temperatures. In the refrigeration system, R134A and R513A refrigerants performed approximately equally. Furthermore, it was noted that R513A had a lower Direct Emission (DE) value compared to R134A. Since R513A does not possess flammable properties, it can be used in systems designed for R134A without needing any modifications [4].

Choi et al., a novel method was developed to evaluate the environmental impacts of household refrigerators in terms of LCCP. This study provided an energy consumption model for this study refrigerator covering three typical single evaporator refrigerators. The authors used experimental data from series, bypass, and parallel circuit refrigerators to calculate energy consumption in dual evaporator refrigerators. The study underlined that in terms of LCCP, the performance of the system and equipment production emissions were influential factors in the lifetime CO_2 emissions. Several findings were discussed, including the approximate 14% reduction in CO_2 emissions when a dual evaporator cycle was used instead of a single evaporator in the refrigeration cycle in the results. Additionally, they noted that using aluminum instead of steel for condenser materials could result in approximately a 2.5% reduction in CO_2 emissions, applying vacuum insulation panels on both sides of the refrigerator for insulation could lead to about a 7% reduction in CO_2 emissions, and using renewable energy sources for energy consumption could potentially reduce emissions by approximately 20%. These findings underscore the significance of design choices and technologies in mitigating the environmental impact of household refrigerators [5].

Wan et al., were investigated 11 different cities and five different refrigerants in conjunction with various impact parameters using a 10.5 kW air conditioner. They evaluated these parameters through Life Cycle Climate Performance (LCCP) analysis and compared the results. The study explored the potential of using low GWP refrigerants, such as R-290, R-32, R-452B, and R-466A, as alternatives to R410A. Experimental findings concluded that emission factors were important for countries with high annual energy consumption. R-290, R-32, R-452B, and R-466A were determined as excellent alternative refrigerants to R-410A for countries with low emission factors. It was also noted that R-32, R-452B, and R-466A for LCCP results were similar, while R-410A had the highest LCCP value. The study estimated that LCCP values could be reduced by up to 60% by replacing R-410A with R-290. These findings highlighted the importance of choosing environmentally friendly refrigerants and the important role can play in reducing carbon emissions [6].

In another study, Choi et al. carried out on LCCP for cooling and heating systems in five different cities in South Korea. The study investigated using refrigerant systems for cooling, gas boilers for heating, and heat pumps for space heating. It has been found that using refrigerant systems for cooling, a gas boiler for heating, and a heat pump for space heating, can reduce CO_2 emissions by approximately 11-17%. Additionally, the use of refrigerants with low global energy potential was also observed, along with various cycle parameters and weather conditions. The study noted that low-GWP refrigerants would reduce direct emissions by reducing the charge amount compared to R410A. Besides, adding a flash tank to the vapor cycle using R410A has been shown to increase energy efficiency and reduce CO_2 emissions by 7-10% [7].

Ergün et al. investigated R-417A and R-438A refrigerants as alternatives to R-22 refrigerant, which is widely used in cooling systems. Additionally, the performance of these refrigerants was compared by evaluating the energy, exergy, and COP values of the system for different evaporation temperatures. The results indicated that among the three refrigerants evaluated, R-438A had higher COP values than R-417A and R-22. Therefore, R-438A is the best alternative to R-22 refrigerant in terms of performance [8].

Özgür analyzed the exergy efficiency and performance of R-1234yf and R-1234ze refrigerants, which are alternatives to R134a refrigerant in the refrigerant cycle. The efficiency and exergy performance of R-134a, R-1234yf, and R-1234ze refrigerants were compared in the same cycle and operating range.

The results showed that the cycle efficiency and exergy performance values of R-134a and R-1234ze refrigerants were the same. However, when R-1234yf refrigerant was used, higher values were obtained compared to the other two refrigerants. The study also reported that R-1234yf more efficient and effective alternative to R-134a in cooling systems [9].

Additionally, Leck investigated the design of cooling systems and heat pumps for residential and light commercial vehicles and medium-temperature cooling applications in the simulation program. R22, R407C, R32, HFO-1234yf, DR-11, DR-4, DR-3, DR-5, and DR-9 were tested, and an energy and LCCP assessment was conducted. The study found that HFO-1234yf had a lower LCCP than R410A and R404A due to its low GWP. However, DR-5 provided the best energy and LCCP performance among the tested refrigerants. [10].

Various protocols indicated that CFC (Chlorofluorocarbon) and HCFC (Hydrochlorofluorocarbon) refrigerants will be restricted in the future, and alternatives to these refrigerants must be developed. In this regard, a study was conducted to evaluate HFC (hydrofluorocarbon)-based R404A and R410A refrigerants, as well as HFO (hydrofluoroolefin)-based R1234yf refrigerant, for different evaporative temperatures in cooling systems. For this purpose, calculations of $kgCO_2$ equivalent were conducted by utilizing the first and second laws of thermodynamics, performance coefficients, exergy efficiency, and exergy destruction, along with the LCCP method, and the results were compared.

II. MATERIAL METHOD

Due to changing conditions since 1830, including environmental impacts and legal obligations, many refrigerants have been developed and used in systems depending on the desired characteristics [11]. When examining first-generation refrigerants, any available refrigerant was used for cooling. In second-generation refrigerants, characteristics like safety and durability became prominent. Third-generation refrigerants focused on protecting the ozone layer, leading to the use of refrigerants that do not harm the ozone layer. Due to increasing concerns about global warming, fourth-generation refrigerants currently in use are required to have conditions such as an ODP of 0, low GWP, high efficiency, and disappears into the atmosphere quickly [13].

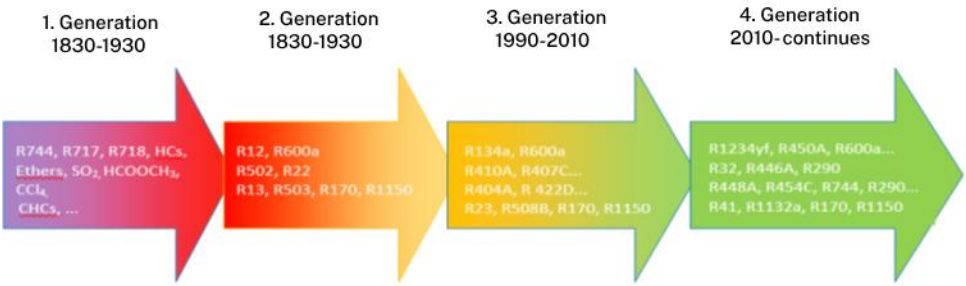


Figure 1. *Development of Refrigerants Over the Historical Period [12]*

The chemical composition, mass quantities, Ozone Depletion Potential, and Global Warming Potential values of the refrigerants used are provided in Table 1.

Table 1. *Physical and Thermodynamic Properties of Refrigerants Classified as HFC and HFO [14]*

	R404A	***R410A***	***R1234yf***
Chemical Composition	CF3CHF3, CF3CH3, CFcCH2F (52% R-143a / 44% R-125 / 4% R-134a)	CH2F2, CF3CHF2 (50% R-125 / 50% R-32)	CF3CF=CH2
Molecular Weight (g/mol)	97.6	72.4	114.04
Critical Temperature (°C)	72.05	71.36	95
Critical Pressure (MPa)	37.29	49.02	3.382
Standard Boiling Point (°C)	-51.2	-60.6	-29
Safety Class	A1	A1	A2L
ODP	0	0	0
GWP	3922	2088	4

In this study, refrigerants with high Global Warming Potential, such as R404A and R410A, as well as the so-called new generation refrigerant with low GWP, R1234yf, were used with the design parameters specified in Table 2. The Genetron Properties software was employed, and a simple refrigeration cycle was selected within the program to analyze this system's energy, exergy, and LCCP. The system's coefficient of cooling performance and exergy efficiency were calculated under the same operating conditions using different refrigerants. Figure 2 provides a schematic representation of the system, and the exergy losses of the system components were calculated.

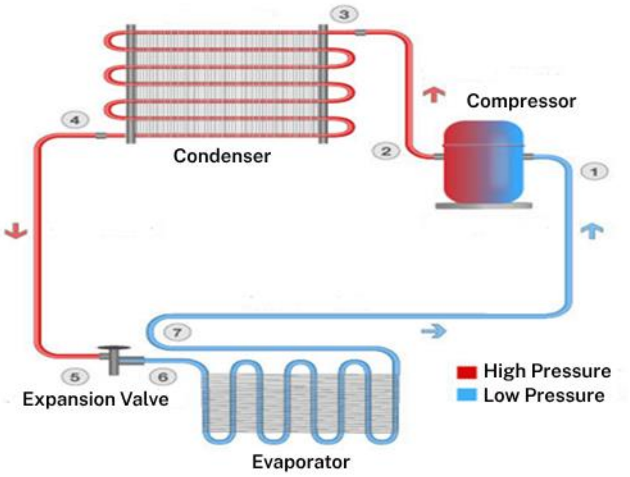


Figure 2. *Schematic view of the refrigeration cycle*

The simulation program selected a 2 kW refrigeration system. The electrical and mechanical efficiency of the compressors in the system was assumed to be 98% and 88%, respectively. It was assumed that the system operates in an open channel flow and that there is no pressure drop in the pipes used. The condenser temperature in the system was kept constant at 50°C, and the evaporator temperature was varied at -30, -15, -5, and 0°C according to the Eurovent standard for separate refrigerant analysis [8].

III. ANALYSIS

A. Thermodynamic Analysis

The energy equations applied to the system components, considering the cycle points shown in Figure 2, for the first-law analysis of the cooling system are provided below.

Condenser heat load:

$$\dot{Q}_{kond} = \dot{m}.(h_3 - h_4) \tag{1}$$

Evaporator heat load:

$$\dot{Q}_{evap} = \dot{m}.(h_7 - h_6) \tag{2}$$

Power of compressor:

$$\dot{W}_{komp} = \dot{m}.(h_2 - h_1) \tag{3}$$

Electrical power consumed by the compressor:

$$\dot{W}_{komp,el} = \frac{\dot{W}_{komp}}{\eta_{el}.\eta_{mek}}) \tag{4}$$

Coefficient of performance of the refrigeration system:

$$COP_C = \frac{\dot{Q}_{evap}}{\dot{W}_{komp,el}} \tag{5}$$

Heating performance coefficient of the refrigeration system:

$$COP_H = \frac{\dot{Q}_{kond}}{\dot{W}_{komp,el}} \tag{6}$$

Exergy is defined as the potential work of a system concerning its surroundings. When the system is balanced with its surroundings, useful work is obtained. The exergy of a system in equilibrium with its surroundings is zero. Exergy transfer between systems occurs through mass, energy, entropy, and power. When a system cannot perform work thermodynamically, the state of the environment is referred to as a "steady state" [15,16]. The steady state of a system implies that the system is in thermodynamic equilibrium with its surroundings. A steady system has the temperature and pressure of its surroundings. It has zero kinetic and potential energy relative to its surroundings and does not react to them. Additionally, no imbalanced magnetic, electrical, or surface tension effects exist between the system and its surroundings. The steady state's characteristics are denoted by zero subscripts, such as, P_0, T_0, h_0, u_0, s_0. Unless otherwise specified, the steady state temperature and pressure are assumed to be T_0 = 25 ℃ and P_0 = 1 atm (101.325 kPa) [15].

In the case where kinetic and potential energy are neglected for a flowing system, the specific exergy per unit mass is calculated as follows:

$$\psi = \text{h} - h_0 - T_0(s - s_0) \tag{7}$$

The equation, when multiplied by the mass flow rate of the refrigerant, is as follows:

$$\dot{Ex} = \dot{\text{m}}[(\text{h} - h_0) - T_0(s - s_0)] \tag{8}$$

The exergy balance and exergy loss of the components in the cooling system can be calculated as follows. The exergy balance equation for the condenser is as follows:

$$\dot{Ex}_{y\imath k.kond.} = \dot{Ex}_3 - \dot{Ex}_4 - Q_{kond}(1 - \frac{T_0}{T_{kond}}) \tag{9}$$

The exergy balance equation for the evaporator is as follows:

$$\dot{E}x_{yık.evap.} = \dot{E}x_7 - \dot{E}x_6 - Q_{evap}(1 - \frac{T_0}{T_{evap}}) \quad (10)$$

The exergy balance equation for the compressor is as follows:

$$\dot{E}x_{yık.komp.} = \dot{E}x_2 - \dot{E}x_1 - \dot{W}_{komp,el} \quad (11)$$

Expansion valve's exergy balance equation:

$$\dot{E}x_{yık.GV.} = \dot{E}x_5 - \dot{E}x_6 \quad (12)$$

The second-law exergy efficiency of the refrigeration system is expressed by the following equation:

$$\eta_{Ex} = \frac{\dot{E}x_3 - \dot{E}x_4}{W_{komp,el}} \quad (13)$$

The equation for the total exergy destruction in the system can be expressed as follows:

$$\dot{E}x_{yık.Toplam} = \dot{E}x_{yık.kond.} + \dot{E}x_{yık.komp.} + \dot{E}x_{yık.evap.} + \dot{E}x_{yık.GV.} \quad (14)$$

B. LCCP Analysis

LCCP is a valuation method used to assess the impact of HVAC (Heating, Ventilation, and Air Conditioning) systems on global warming over their entire lifecycle. It considers both direct and indirect emissions incurred throughout the system's life, from production to use, maintenance, and final disposal. Direct emissions include all effects of the refrigerant released into the atmosphere during the system's lifespan, encompassing annual leaks and losses that occur when the device is disposed of. Indirect emissions, on the other hand, cover emissions originating from production processes, energy consumption, and facility disposal [16]. LCCP is divided into two main groups: direct emissions and indirect emissions. Figure 3 illustrates the LCCP categories. Each category within the given main groups is calculated separately, and the results are expressed in $kgCO_2$ equivalent.

$$\text{LCCP} = \text{DE}(\text{CO}_{2,\text{Direct}}) + \text{EE}(\text{CO}_{2,\text{Indrirect}}) \quad (15)$$

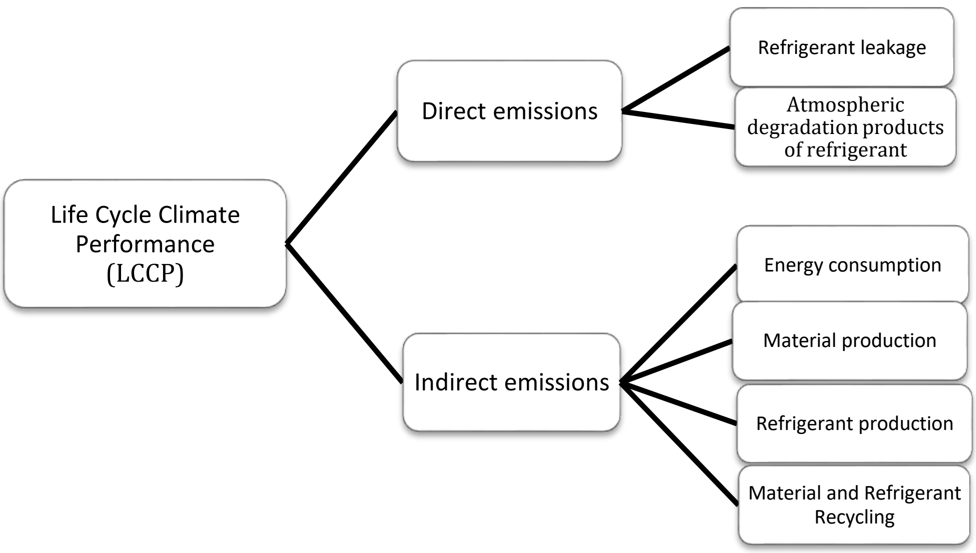


Figure 3. *Life Cycle Climate Performance (LCCP) Categories*

Direct emissions arise from the use of vapor compression systems. They result from the effects of the refrigerant released into the atmosphere during the system's operational life (annual refrigerant leakage due to leaks, refrigerant losses at the end of the system's life, and reaction products from a refrigerant breakdown in the atmosphere). Direct emissions from vapor compression systems ($CO_{2,Direct}$) can be calculated using the following equation [16]:

$$CO_{2,Direct} = C * (L * ALR + EOL) * (GWP + GWP_{adp}) \quad (16)$$

Where C represents the refrigerant charge used (kg), L is the operating lifetime of the system (years), ALR is the annual refrigerant leakage rate of the refrigerant used (%), and EOL is the refrigerant leakage rate at the end of the device's lifetime (%). GWP denotes the global warming potential of the refrigerant ($kgCO_2eq/kg$), and GWP_{adp} stands for the global warming potential arising from the breakdown of the refrigerant in the atmosphere ($kgCO_2eq/kg$). Indirect emissions encompass all emissions from the production to disposal of a unit and this includes all emissions during manufacturing, usage, and recycling processes. Indirect emissions are calculated as per Equation 17.

$$CO_{2,Indirect} = L * AEC * EM + \Sigma(m\ MM) + \Sigma(m_r\ RM) + C * (1 + L * ALR) * RFM + C * (1 - EOL) \quad (17)$$

Where AEC represents the annual energy consumption of the system (kWh/year), EM denotes the emission factor for electricity production ($kgCO_2eq/kWh$), m signifies the mass of the cooling unit used (kg), MM is the material manufacturing emissions ($kgCO_2eq/kg$), m_r stands for the mass of recycled material (kg), RM represents the emissions from recycled material ($kgCO_2eq/kg$), and RFM signifies the emissions from refrigerant manufacturing.

In this study, R404A, R410A, and R1234yf were used for each refrigerant, and experimental data were obtained by inputting the following assumptions into the simulation program. Energy, exergy, and LCCP analyses were conducted using the obtained data. The assumptions taken are provided in Table 3.

Table 3. *Assumptions Made for Energy, Exergy, and LCCP Analyses*

Description	Value
Cooling capacity	2 kW
System service life (L)	15 Years
Annual refrigerant leakage rate (ALR)	2.5%
Refrigerant leakage rate at the end of device life (EOL)	15%
Heat pump unit mass (m)	100 kg
Condenser temperature	50°C
Evaporator temperature	-30, -15, -5, 0°C
Compressor electrical efficiency	98%
Compressor mechanical efficiency	88%
Superheating	5°C
Subcooling	5°C

IV. RESULTS

Analyses were performed for R404A, R410A, and R1234yf refrigerants in a vapor compression refrigeration cycle under the same operating conditions. Genetron Properties software was used to calculate the thermodynamic properties of the refrigerants. The analysis results, including energy, exergy, and Life Cycle Climate Performance (LCCP) parameters, were obtained. These results were evaluated and presented in tables and graphs.

The change in compressor power when the evaporation temperatures of R404A, R410A, and R1234yf refrigerants were varied between -30 °C and 0 °C is shown in Figure 4. As can be seen from the figure, in this range of evaporation temperatures, R404A refrigerant has the highest compressor power consumption. At -30 °C evaporation temperature, the refrigerant compressor energy consumptions are as follows: 1.328 kW for R404A, 1.245 kW for R1234yf, and 1.199 kW for R410A. Compared to R1234yf, R404A consumes 6.24% more power, and compared to R410A, it consumes 9.71% more power. For R404A, at -30 °C, it consumes 1.328 kW, and at 0 °C, it consumes 0.596 kW, resulting in a difference of 0.732 kW. R410A consumes 1.199 kW at -30 °C and 0.574 kW at 0 °C, with a difference of 0.625 kW. R1234yf consumes 1.245 kW at -30 °C and 0.555 kW at 0 °C, resulting in a difference of 0.69 kW. As the evaporation temperature increases, the power consumption of all refrigerants decreases.

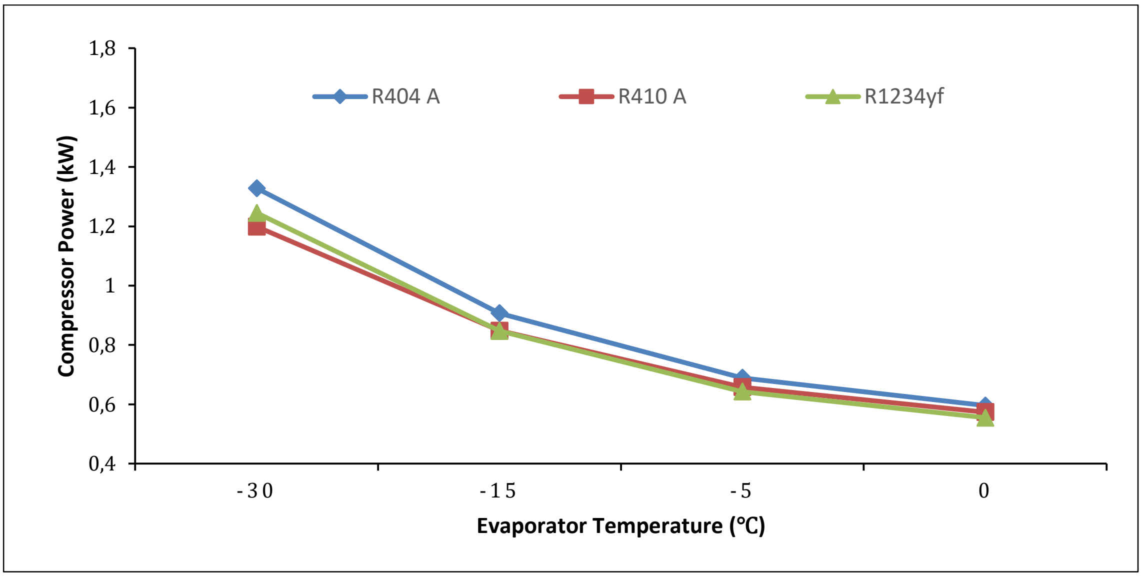


Figure 4. *Compressor energy consumption of refrigerants*

When the evaporation temperatures of R404A, R410A, and R1234yf refrigerants are varied between -30°C and 0°C, COP for heating and cooling are shown in Figure 5. When investigating the heating and cooling COP values, it can be observed that R404A has a 10% increase, and R1234yf has a 7% increase compared to R410A. These COP values are directly proportional to the evaporation temperature, and the compressor energy consumption is inversely proportional. For R404A, the cooling COP values range between 1.5 and 3.3, and the heating COP values range between 2.5 and 4.3. For R410A, the cooling COP values range between 1.66 and 3.48, and the heating COP values range between 2.66 and 4.48. As for R1234yf, the cooling COP values range between 1.60 and 3.60, and the heating COP values range between 2.60 and 4.60.

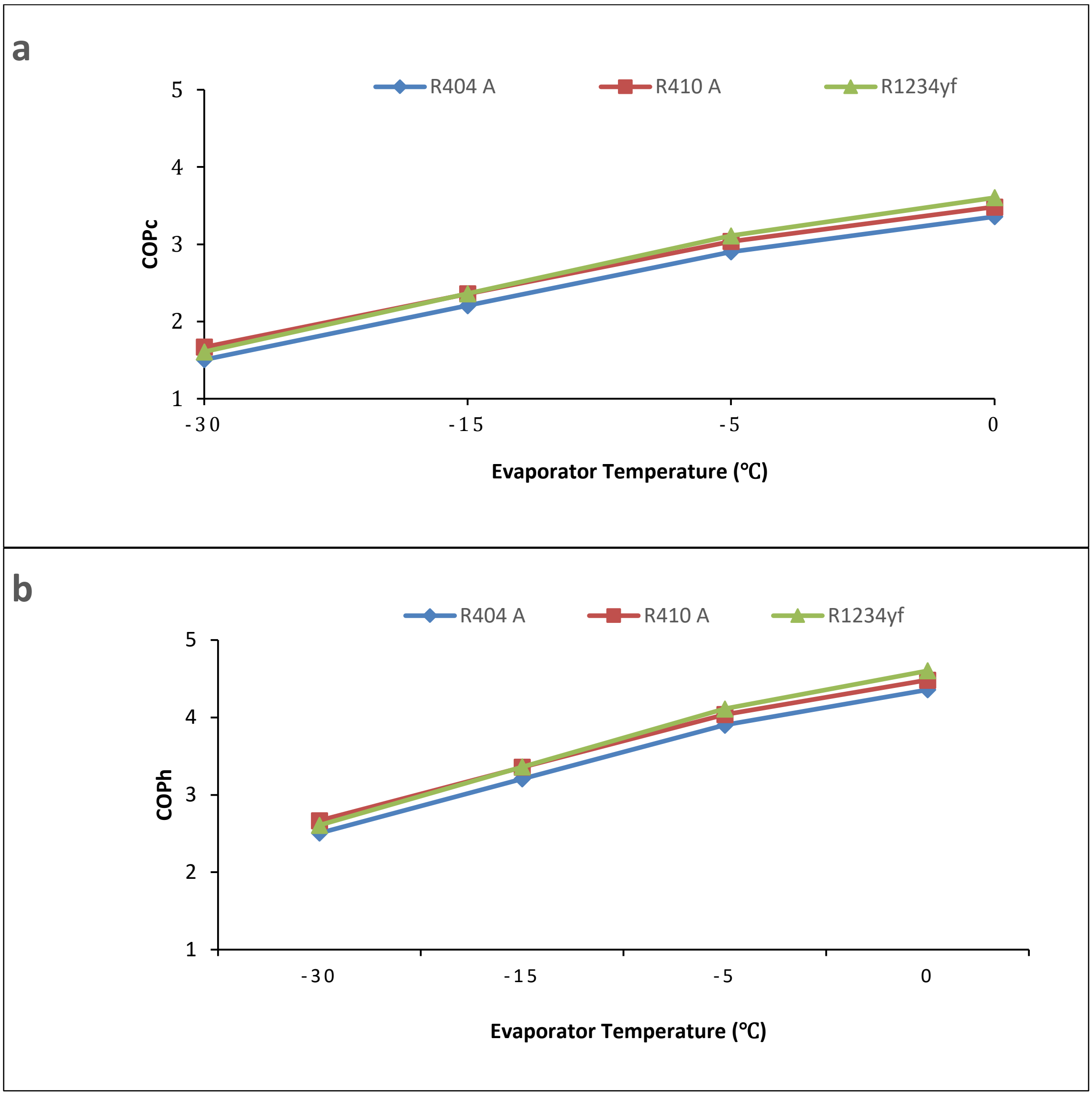


Figure 5. *Change in cooling COP values (a) and heating COP values (b) of the refrigeration system*

When the evaporation temperatures of R404A, R410A, and R1234yf refrigerants are changed between -30°C and 0°C, the change in the system's condenser power is shown in Figure 6. As seen in the figure, the highest condenser load was found to be 3.3 kW for R404A refrigerant, 3.244 kW for R1234yf refrigerant, and 3.199 kW for R410A refrigerant at -30°C. Increasing the evaporation temperature of the refrigerants resulted in a decrease in the condenser capacities. With an increase in the condensation temperature, the compression ratio of the compressor will increase, and the flow rate of the refrigerant circulating in the system will decrease, leading to a partial decrease in the cooling capacity.

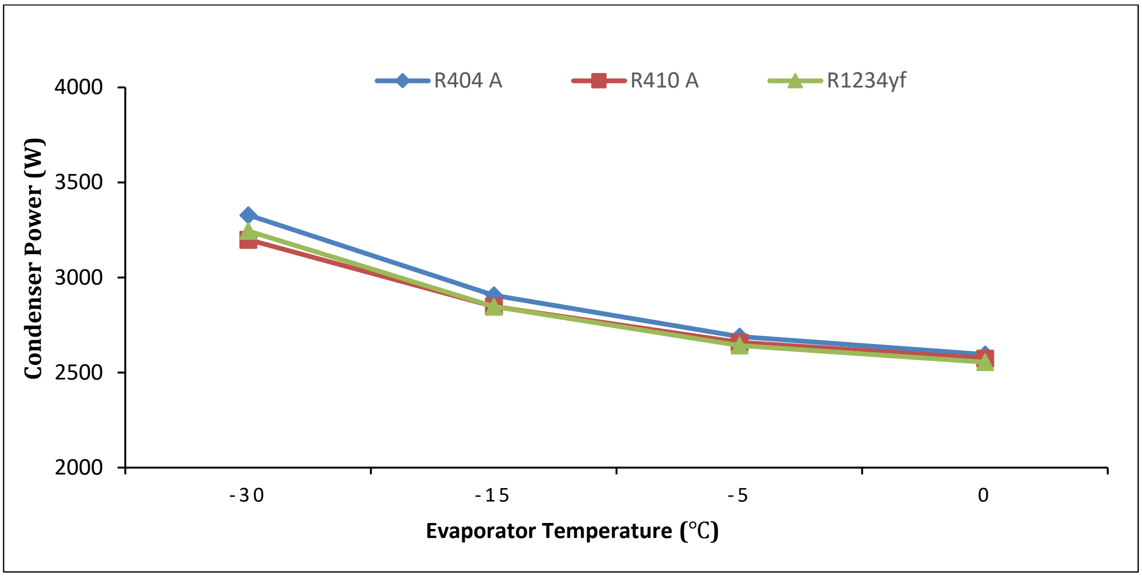


Figure 6. *Condenser powers for refrigerants in the system*

Figure 7 illustrates the change in the total exergy destruction of the system when R404A, R410A, and R1234yf refrigerant evaporation temperatures are varied between -30°C and 0°C. The highest total exergy destruction is 3.13 kW for R404A, 2.96 kW for R1234yf, and 2.775 kW for R410A at -30°C. As the evaporation temperatures decrease, the total exergy destruction in the system increases. The total exergy destruction is inversely proportional to the evaporation temperature.

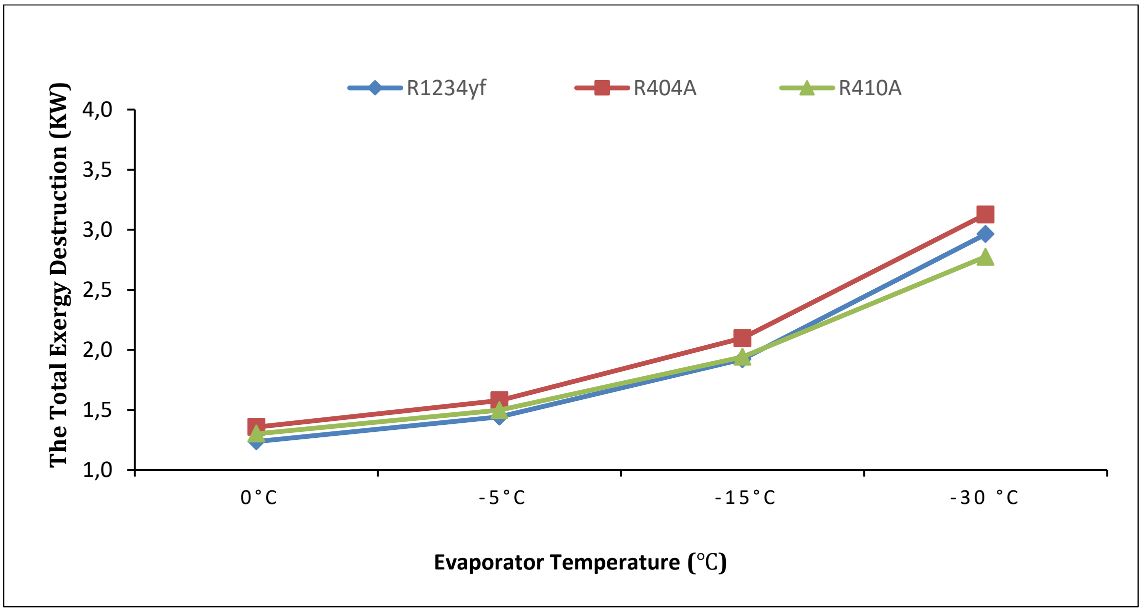


Figure 7. *Exergy destruction of the systems*

When R404A, R410A, and R1234yf refrigerants evaporation temperatures between changed -30 ℃ and 0 ℃, exergy efficiency changes are shown in Figure 8. The exergy efficiency of the refrigeration system is observed to vary between 26% to 29.4% for R404A refrigerant, between 27% to 32.5% for R410A refrigerant, and between 28% to 31.5% for R1234yf refrigerant.

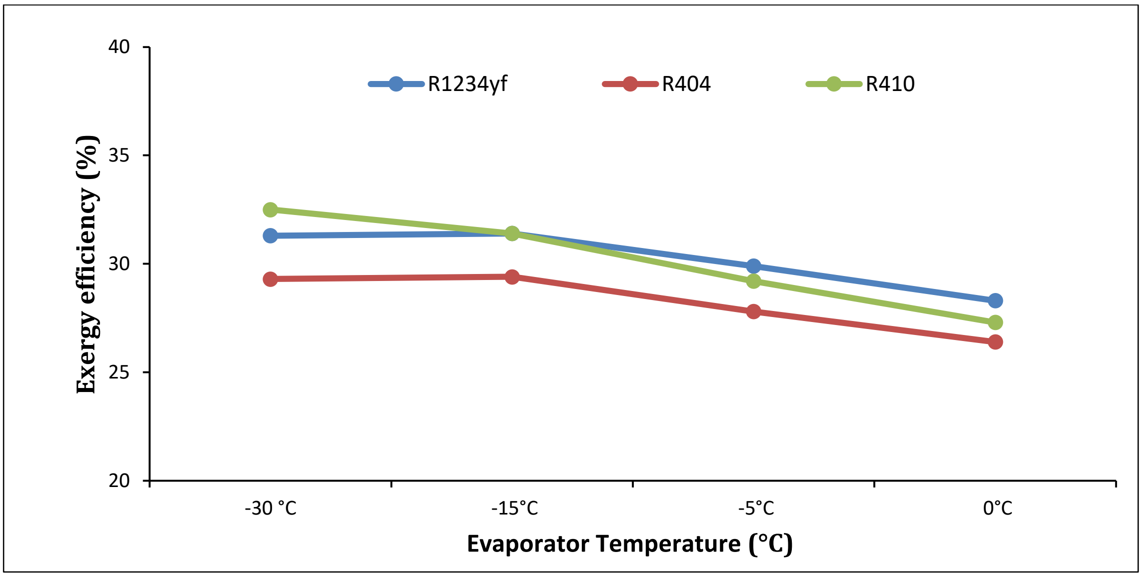
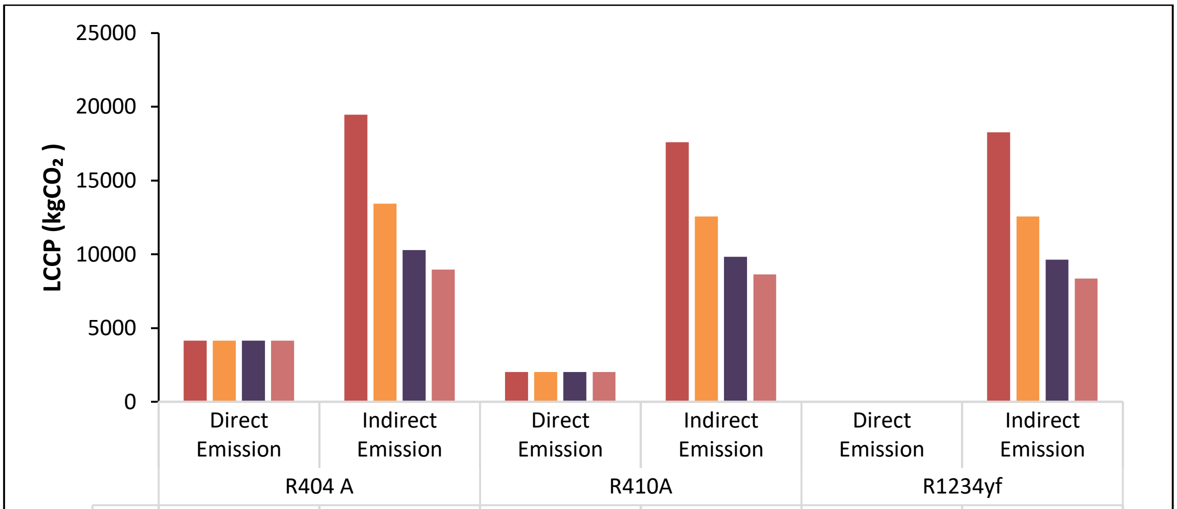


Figure 8. *Exergy efficiency of the systems*

LCCP analysis based on the evaporation temperatures of the refrigerants is shown in Figure 9. As the evaporation temperature decreases, an increase in the LCCP value is observed. When the evaporation temperature is changed between 0 °C and -30 °C, the LCCP values for R404A refrigerant range from 13102 $kgCO_2$ to 23611 $kgCO_2$, for R410A refrigerant range from 10650 $kgCO_2$ to 19622 $kgCO_2$, and R1234yf refrigerant range from 8370 $kgCO_2$ to 18275 $kgCO_2$. The direct emission ratios in the total emission values of R404A, R410A, and R1234yf refrigerants are approximately 20.3%, 11.7%, and 0.05%, respectively.



	R404 A		R410A		R1234yf	
	Direct Emission	Indirect Emission	Direct Emission	Indirect Emission	Direct Emission	Indirect Emission
-30	4140,15	19470,98	2020,20	17602,63	4,20	18271,23
-15	4140,15	13427,34	2020,20	12563,87	4,20	12557,76
-5	4140,15	10297,85	2020,20	9836,33	4,20	9629,25
0	4140,15	8962,79	2020,20	8630,47	4,20	8365,97

Figure 9. Detailed comparison of LCCP analysis according to refrigerant evaporation temperatures

The LCCP analysis used wind energy, a renewable energy source, to demonstrate its indirect emissions impact on the cooling cycle. The emission value for wind energy was considered to be 0.1237 $kgCO_2$

per kWh, with an average emission value of 0.440 $kgCO_2$ per kWh. Keeping the evaporation temperature at 0°C and the condenser temperature at 50°C constant, a comparison was made between the average and emission values for wind energy. According to the comparison in Figure 10, when wind energy is used for electricity generation, there is a reduction of 17.79% $kgCO_2$ in R404A refrigerant, 41.68% in R410A refrigerant, and 65.88% in R1234yf refrigerant.

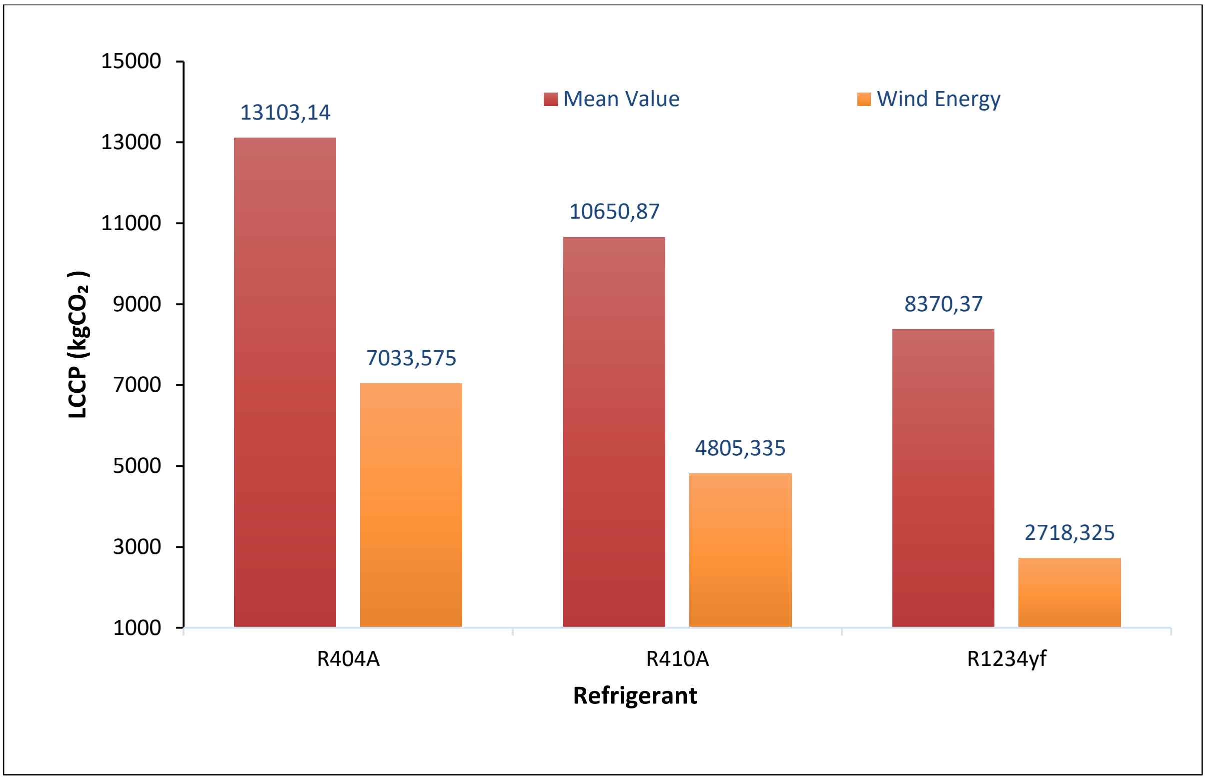


Figure 10. *LCCP comparison based on average emission values and wind energy emission values*

V. CONCLUSION

In this study, a simple vapor compression refrigeration cycle system was designed using the Genetron simulation program. Due to the phase-out of high GWP refrigerant R404A in new devices, an energy, exergy, and life cycle climate performance (LCCP) analysis was conducted for the lower GWP refrigerant R410A and the new-generation refrigerant R1234yf, in comparison with R404A. The results are summarized below, and recommendations have been made.

- The COP values for heating and cooling are highest at an evaporation temperature of -30°C for R410A refrigerant and at an evaporation temperature range of -15°C to 0°C for R1234yf. As the evaporation temperature of refrigerants increases, the heating and cooling COP of refrigerants also increases.

- While the highest exergy efficiency was calculated for R410A at -30°C evaporation temperature, the highest exergy efficiency was found in R1234yf refrigerant between -15°C and 0°C evaporation temperature.

- The lowest exergy efficiency is observed for the refrigerant R404A. The exergy efficiency of R404A refrigerant is approximately 6.6% lower than that of R1234yf and R410A refrigerants.

- Total exergy destruction of all systems was at the lowest level with R1234yf at -30°C, followed by R410A and R404A. As the evaporation temperature decreases, the exergy destruction of the system increases. Exergy destruction was inversely proportional to the evaporation temperature.

- LCCP analysis, the direct emission values of all refrigerants are approximately less than 1% for R1234yf, approximately 12% for R410A, and approximately 20% for R404A. More than 80% of the total emission value of refrigerants is due to indirect emissions.

- There is approximately a 17% reduction in kgCO_2 emissions for R404A compared to R410A at an evaporation temperature of -30°C and approximately a 23% reduction compared to R1234yf. A comparison was made using an LCCP analysis with parameters held constant at an evaporation temperature of 0°C and a condenser temperature of 50°C, comparing the average emission value with the wind energy emission value. A comparison of the average emission value with the wind energy emission value reveals reductions in kgCO_2e emissions of approximately 18% for R404A, 42% for R410A, and 66% for R1234yf.

- Almost all of the indirect emissions are attributed to the energy consumption of the compressor in the cooling system. It is essential to use refrigerants with low charge amounts and low GWP values to improve efficiency and reduce the energy the compressor. Additionally, utilizing environmentally friendly energy sources like renewable energy for generating the electricity needed to work the compressor is crucial.

In conclusion, based on the energy, exergy, and LCCP analysis results, it is feasible to use R410A or R1234yf refrigerants as alternative refrigerants in cooling systems currently using R404A. The necessary adjustments and appropriate equipment selection are required for these transitions. According to the data obtained, R1234yf refrigerant exhibits lower energy consumption and higher exergy efficiency compared to R404A and R410A. Furthermore, R1234yf has a lower LCCP value than R404A and R410A. Therefore, R1234yf refrigerant is considered a better alternative regarding energy efficiency and environmental impact.

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NOMENCLATURE

CO_2 : Carbon Dioxide
m : Mass
Al : Aluminum
T : Temperature
ψ : Specific Energy
Ex : Exergy
Q : Heat
0 : Steady State Reference Point
W : Work
η : Efficiency
s : Entropy
h : Enthalpy

ABBREVIATIONS

GWP : Global Warning Potential
GWP_{adp}: Global Warning Potential of Refrigerants Degrading in the Atmosphere

ODP : Ozane Depletion Potential
LCCP : Life Cycle Climate Performance
COP : Coefficient of Performance
HVAC : Heating Ventilation Air Conditioning
HC : Hydrocarbon
CFC : Chlorofluorocarbon
HCFC : Hydrochlorofluorocarbon
HFC : Hydrofluorocarbon
HFO : Hydrofluoroolefin
UNEP :United Nations Environment Programme
WMO : World Meteorological Organization
UNCED : United Nations Conference on Environment and Development
UNFCCC :United Nations Framework Convention on Climate Change
DE : Direct Emission
EE : Indirect Emission
C : Refrigerant Charge Amount
L : System Operating Life
ALR : Annual Refrigerant Leakage Rate
EOL : End of Life Refrigerant Leakage Rate
AEC : Annual Energy Consumption
EM : Electricity Generation Emission Value
MM : Material Manufacturing Emissions
mr : Recycled Material Mass
RM : Recycled Material Emissions
RFM : Refrigerant Manufacturing Emissions
RFD : Refrigerant Disposal-Related Emissions