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Research Article

COMPARATIVE THERMODYNAMIC AND ENVIRONMENTAL ANALYSIS OF VAPOR COMPRESSION REFRIGERATION SYSTEM USING C-PENTANE AS REFRIGERANT

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ABSTRACT: The selection of refrigerant is one of the most important parameters when designing a cooling system. Hydrocarbon refrigerants have low primary energy requirements for effective cooling capacity and favorable thermodynamic properties that reduce both direct and indirect greenhouse gas emissions. In this study, a comparative performance and environmental analysis of the vapor compression refrigeration cycle using C-Pentane as the refrigerant was performed. The cooling performance and environmental effect of C-Pentane has been compared with the cooling performance and environmental effect of R134A, R407C and R404A refrigerants in the cooling system. During the analysis, the cooling system was examined under different operating conditions. The highest coefficient of performance (COP) value in the analysis was 6.485 for the refrigeration cycle using C-Pentane, and this value was obtained at 0 ^oC evaporator temperature and 25 ^oC condenser temperature operating condition. According to the Life Cycle Climate Performance (LCCP) analysis for refrigerants, the lowest total emission value belongs to C-Pentane. Direct Emission (DE) value and indirect emission (IE) value of C-Pentane are 57.5 $kgCO_2$ and 24928.04 $kgCO_2$, respectively.
Keywords: C-Pentane, Environmental Analysis, Thermodynamic Analysis, Refrigeration System.

1. INTRODUCTION

Hydrocarbons are called natural coolants because they occur in the matter cycle in the soil. For example, they are by-products of natural gas production or oil refineries. Hydrocarbons are highly flammable, combustible and virtually odorless. Cooling systems using natural refrigerants can play an important role against global warming. Hydrocarbon refrigerants have become important for refrigeration systems, as halogenated and fluorinated refrigerants cannot be used in a very short time. The most known hydrocarbon fluids are n-butane, iso-butane, propane, propylene, n-pentane and C-pentane which has been the most preferred in recent years. C-pentane is preferred as a refrigerant used especially in cooling systems and thermal balancing applications. This refrigerant is often used in place of other refrigerants such as R-12 and R-134a. C-pentane has an ozone depletion potential (ODP) of 0 and a global warming potential (GWP) of 5. This feature is quite remarkable when compared to other refrigerants. C-pentane was developed to reduce the use of refrigerants such as chlorofluorocarbon (CFC) and hydrofluorocarbon (HFC), which damage the ozone layer. Therefore, it is an environmentally friendly refrigerant. C-pentane has high heat transfer properties. Therefore, this fluid provides more effective and efficient working conditions in cooling systems. Additionally, C-pentane is an economical option compared to many other refrigerants. Because production costs are generally low, this makes it preferred in industrial applications. C-pentane also has some disadvantages. C-pentane is a highly flammable refrigerant. Therefore, one should be careful about fire safety and take appropriate safety precautions. Additionally, due to its flammability, the storage and transportation of C-pentane must comply with certain safety standards. This may require additional security measures in transactions. In addition to being flammable, C-pentane can, in some cases, contribute to global warming by acting as a greenhouse gas among gases in the atmosphere. However, this effect is generally lower compared to other refrigerants. Kulkarni et al. [1] studied the performance of environmentally friendly refrigerants in cooling systems. It has been shown that these refrigerants have good performance, and that their use with nanofluids will make the performance even better. Liu et al. [2] determined that the use of mixed refrigerants instead of pure refrigerants in the refrigeration system is a factor that increases performance. Zhao et al. [3] performed energy and exergy analyses using R600a/R601a mixtures in the combined power and refrigeration cycle. He et al. [4] performed performance analysis for different operating conditions in the cascade cooling system. They determined that mixed refrigerants increased the cooling system performance. Sun et al. [5] investigated the performance of a single refrigerant cascade refrigeration system consisting of refrigerant pairs. The results determined that COP in conventional cascade refrigeration system can be improved by using single refrigerant pairs.

C-pentane is an environmentally friendly refrigerant as it is relatively harmless to the ozone layer and does not contribute to global warming. C-pentane has a good heat transfer capacity and provides high energy efficiency due to this feature.

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In recent years, C-pentane is the most preferred refrigerant in many cooling devices, especially home and commercial refrigerators, freezers, and air conditioning systems. Additionally, C-pentane is an economical refrigerant option. Being cost-competitive has an impact on the preferences of industries and consumers. Therefore, in this study, the energy analysis and environmental impact of the vapor compression refrigeration system using C-pentane, one of the hydrocarbon refrigerants that has stood out with both its thermodynamic and environmental properties in recent years, was made in comparison with R134A, R407C and R404A. Cooling systems using C-pentane, which is the subject of this study, also have significant advantages in terms of operating costs. It is seen that the critical temperature of C-pentane is larger than that of the other fluids used in the study. The critical temperature of refrigerants is an important physical property both in industrial applications and in daily use. In addition, high critical temperature is an expected property of refrigerants. This property of the fluid is a fundamental parameter used in thermodynamic and heat transfer calculations and plays a critical role in understanding and optimising the behaviour of the fluid. C-pentane has been used especially in commercial cooling systems, beverage cabinets and deep freezers in recent years. The properties of the refrigerants in this study are given in Table 1.

Table 1. Properties of refrigerants [6]

Refrigerants	**Molecular Weight (kg/kmol)**	**Critical Temperature (^oC)**	**Critical Pressure (MPa)**	**ODP**	**GWP100**	**GWP_{adp}**	**RFM**	**RFD**
C-Pentane	70.13	238.54	4.515	0	5	-	-	-
R134A	102.032	101.06	4.059	0	1300	1.6	5	-
R407C	86.20	85.76	4.602	0	1530	-	-	-
R404A	97.60	71.96	3.722	0	3260	-	16.7	-

The use of refrigerant C-pentane in both domestic appliances and industrial applications has increased considerably in recent years. This is because this fluid has both good thermodynamic properties and environmental effects are better than conventional refrigerants. In this study, a comparative performance and environmental analysis of a vapour compression refrigeration cycle using C-Pentane as refrigerant is carried out for different operating conditions. The cooling performance and environmental impact of C-Pentane are compared with the cooling performance and environmental impact of R134A, R407C and R404A refrigerants.

The vapor compression refrigeration system (VCRS) goes through the following processes during one cycle; The refrigerant in the saturated vapor state at point 1 is compressed by the compressor. The refrigerant at high temperature and pressure at point two enters the condenser as superheated steam. The refrigerant, which turns into a saturated liquid by throwing its temperature to the environment at point 3, leaves the condenser and enters the throttling valve. In the last stage of the cycle, the low-pressure fluid enters the liquid+vapor phase evaporator and completes the cycle. The representation of the VCRS and the temperature-entropy diagram of the cycle are given in Figure 1.

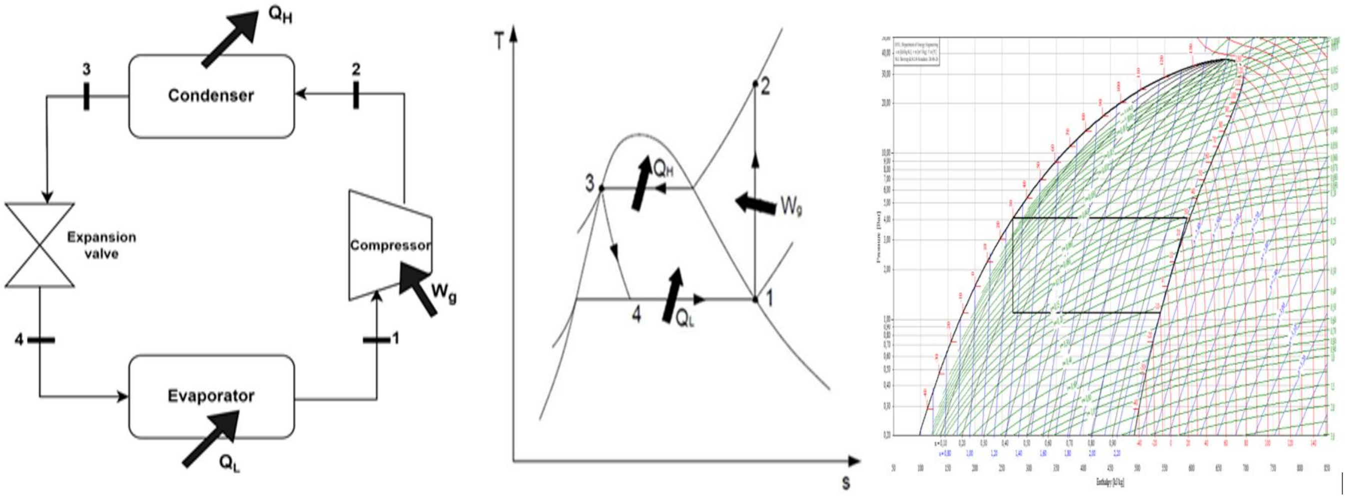

Fig. 1. The VCRS and T-s diagram.

2. THERMODYNAMIC ANALYSIS

The following assumptions are made for the thermodynamic analysis of the vapor compression refrigeration system;
- All elements of the system work in steady state.
- The kinetic and potential energies of the components in the cycle are neglected.
- The isentropic efficiency of the compressor is η_{comp}=70%.
- Heat losses and friction losses are neglected.
- Evaporator temperatures were chosen between 0, -5, -10, -15 and -20 ºC.
- Condenser temperatures were chosen between 25, 30, 35 and 40 ºC.
- Superheating and Subcooling have not been applied in the cooling system.

Due to the limited number of different refrigerants used in the analyzes and the variability of evaporator and condenser temperature ranges, the current results should be considered to be provisional. In this regard, it is emphasized that more studies are needed on this subject, both theoretically and experimentally, in order to reach more reliable results. Evaporator capacity of refrigeration cycle given in Fig. 1 can be determined as follows [7]:

$$\dot{Q}_E = \dot{m}_R(h_1 - h_4) \quad (1)$$

Compressor power is [8-10];

$$\dot{W}_{Comp} = \dot{m}_R(h_2 - h_1) \quad (2)$$

Condenser capacity is;

$$\dot{Q}_C = \dot{m}_R(h_3 - h_2) \quad (3)$$

Coefficient of performance (COP) is the useful heating or cooling rate provided in return for the work done in a cooling system, that is, the ratio of output energy to input energy. The coefficient of performance (COP) of the refrigeration system is defined as the ratio of the evaporator capacity to the compressor power and can be calculated with Eq.4 [11-14];

$$COP = \frac{\dot{Q}_E}{\dot{W}_{Comp}} \quad (4)$$

Environmental analyzes of refrigerants were made according to the Life Cycle Climate Performance (LCCP) method. In LCCP analysis, all emissions of a system throughout its life are calculated. LCCP consists of two main categories; direct emissions and indirect emissions. Direct emissions consist of the effects of refrigerant released into the atmosphere over the life of the refrigeration system, including annual refrigerant loss due to leaks, refrigerant loss at the end of the unit's life, and atmospheric reaction products resulting from the breakdown of refrigerant in the atmosphere. Indirect emissions include emissions resulting from the use of the cooling system throughout its life. These are emissions from electricity generation, emissions from material production, emissions from the production of refrigerants, and emissions from post-life recycling of the unit [15-18].

$$LCCP = Direct\ Emission\ (DE) + Indirect\ Emission\ (IE) \quad (5)$$

$$Direct\ Emission\ (DE) = C\ x\ [(GWP + GWP_{adp})\ x\ (L\ x\ ALR + EOL)] \quad (6)$$

$$Indirect\ Emission\ (IE) = L\ x\ AEC\ x\ EM + MM\ x\ m + RM\ x\ m_r + RFM\ x\ C + L\ x\ ALR\ x\ RFM\ x\ C + C\ x\ (1 - EOL)\ x\ RFD \quad (7)$$

3. RESULTS AND DISCUSSION

The COP of the VCRS using C-pentane, R134A, R407C and R404A was calculated by keeping the condenser temperature constant at 25 ºC and changing the evaporator temperature between 0 ºC and -20 ºC and is given in Fig. 2. It is seen that the highest COP value for all operating conditions given in Fig. 2 is reached in the cycle using C-pentane. This value is 6.485 in operating condition with 0 ºC evaporator temperature and 25 ºC condenser temperature. After C-pentane, the highest COP values were obtained for R134A, R407C and R404A, respectively.

The results of the second analysis made by keeping the condenser temperature constant at 30 ºC and changing the evaporator temperature between 0 ºC and -20 ºC are given in Fig. 3. The highest COP value was obtained for the cycle using C-pentane. This value is 5.4 and was obtained for 0 ºC evaporator temperature and 30 ºC condenser temperature. The lowest COP value is approximately 2.5 for R404A, at -20 ºC evaporator temperature and 30 ºC condenser temperature.

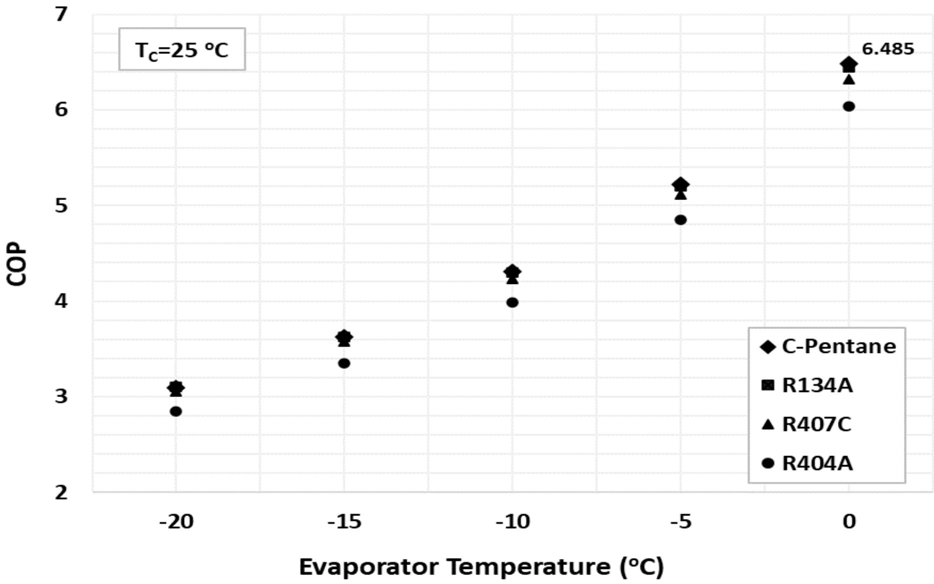

Fig. 2. Variation of COP with evaporator temperature (for T_c=25 ºC).

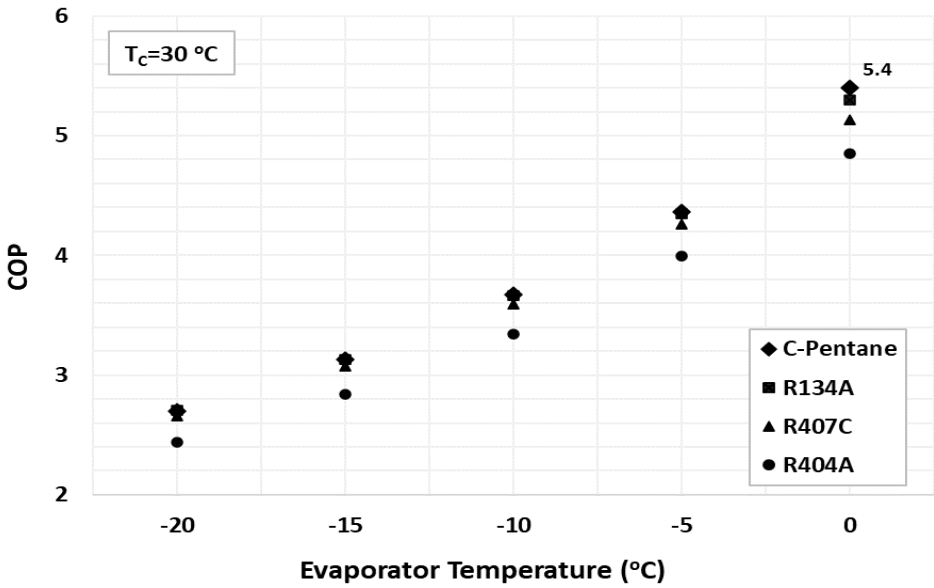

Fig. 3. Variation of COP with evaporator temperature (for T_c=30 ºC).

Another analysis was made by keeping the condenser temperature constant at 35 ºC and changing the evaporator temperature between 0 ºC and -20 ºC, and the results are given in Fig. 4. In the analysis under these operating conditions, the highest COP value is 4.418 and is obtained for the cycle using C-pentane. Then, the highest COP values were calculated for R134A, R407C and R404A, respectively. It is seen both in this analysis and in the two previous analyzes that the COP value decreases as the evaporator temperature decreases. The decrease in evaporator temperature increases the compressor work, which in this case causes a decrease in COP. For example, when the evaporator temperature is -5 ºC, the compressor work is 0.2693 kW, and when the evaporator temperature is -20 ºC, the compressor work is 0.422 kW.

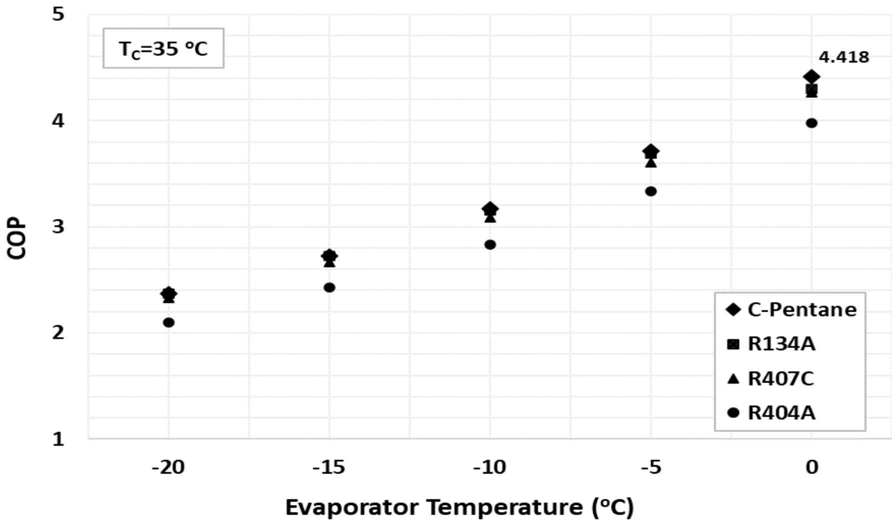

Fig. 4. Variation of COP with evaporator temperature (for T_c=35 ºC).

The final analysis results by keeping the condenser temperature constant at 40 ºC and changing the evaporator temperature are given in Fig. 5. In this analysis, the highest COP value was obtained for the cycle using C-pentane. This value is 3.85 and is obtained for 0 ºC evaporator temperature and 40 ºC condenser temperature. It is seen that the COP values decrease as the evaporator temperature decreases. This result is valid for all refrigerants. Similar to our results, in the study of Ahamed et al., it was concluded that increasing the condenser temperature decreased the COP value, while increasing the evaporator temperature increased the COP values [19].

It has been clearly demonstrated that C-pentane is the most suitable refrigerant for all analyzed operating conditions. However, considering the environmental characteristics, C-pentane stands out when compared to other refrigerants.

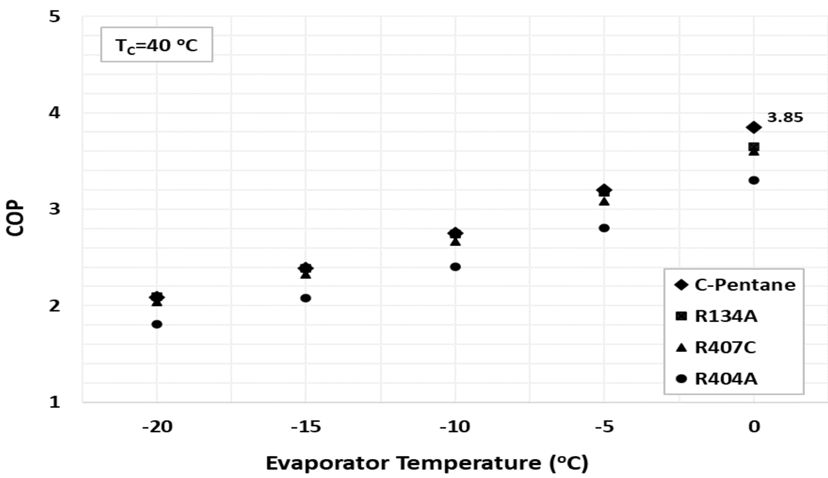

Fig. 5. Variation of COP with evaporator temperature (for T_c=40 ºC).

The results of the LCCP analysis for refrigerants are given in Fig. 6. When Fig. 6 is examined, the lowest emission value is for C-Pentane. The DE value of C-Pentane is 57.5 $kgCO_2$ and the IE value is 24928.04 $kgCO_2$. These values are lower than the values of all other fluids. It is noteworthy that the DE value is 0.23% of the IE value. The ratio of DE value to IE for other fluids is 5.39% for R134A, 12.95% for R404A, and 6.34% for R407C. Almost all of the emission values of refrigerants are due to their indirect emissions. The largest part of indirect emissions originates from energy consumption. Therefore, reducing both the energy consumed in the production of refrigerant and the energy consumption values of the refrigeration systems allows to reduce the total emission values.

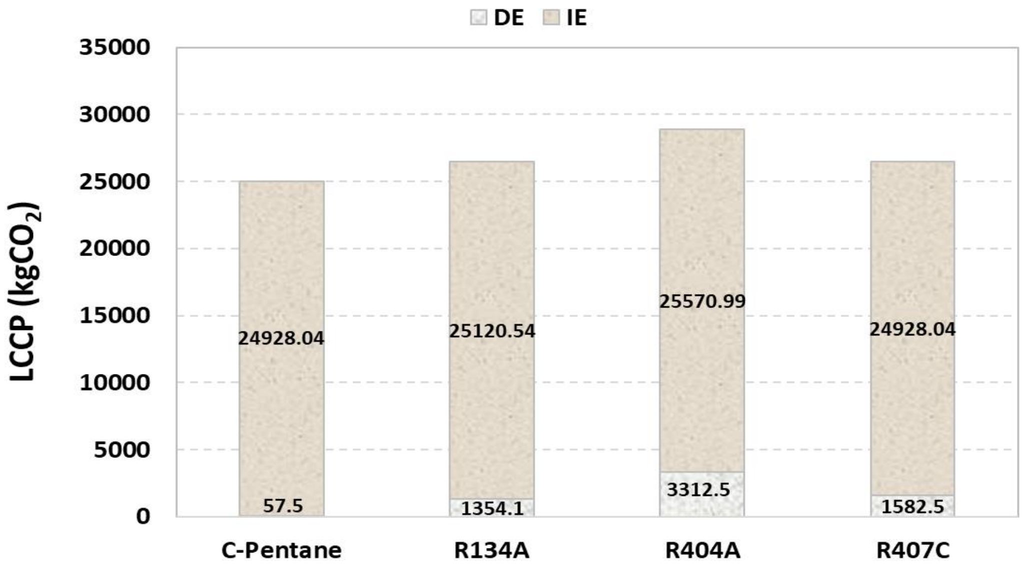

Fig. 6. Comparison of LCCP analysis of refrigerants.

4. CONCLUSIONS

In this study, the energy analysis and environmental effect of the vapor compression refrigeration system using C-pentane, which is one of the leading hydrocarbon refrigerants that has come to the fore with both thermodynamic and environmental properties in recent years, has been made comparatively. For the refrigeration system using C-pentane, R134A, R407C and R404A, it was observed that the COP increased when the evaporator temperature increased, and the COP decreased when the evaporator temperature decreased. However, increasing the condenser temperature also decreases the COP. Similar to our results, in Ref. [20], increasing the condenser temperature decreases the COP value, and increasing the evaporator temperature increases the COP value. Therefore, in order to obtain the most effective COP value, it is very important to determine the most suitable evaporator and condenser temperature as well as the selection of the refrigerant. The highest COP value in the analyzes is 6.485 and this value is obtained under the operating condition of 0 ^oC evaporator temperature and 25 ^oC condenser temperature. Therefore, in order to obtain high efficiency from the vapor compression cooling system using C-pentane, it would be appropriate to operate the system under the operating conditions obtained in the analysis. C-pentane has zero ozone depletion potential (ODP) and GWP100 is 5. Therefore, it is a very good refrigerant for refrigeration cycles and its use should be increased. In addition, according to the LCCP analysis for refrigerants, the lowest total emission value belongs to C-Pentane. DE value and IE value of C-Pentane are 57.5 $kgCO_2$ and 24928.04 $kgCO_2$, respectively. Similar results have been found in the literature. For example, the data in Ref. [21] clearly show that the direct contribution to global warming for the refrigerants in the study (HFOs and their binary mixtures with HFC134a) is negligible compared to the indirect contribution.

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Nomenclature

C	Refrigerant Charge (kg)
GWP	Global Warming Potential (kg CO_{2e}/kg)
GWP_{adp}	GWP of Atmospheric Degradation Product of the Refrigerant (kg CO_{2e}/kg)
L	Average Lifetime of Equipment (yr)
ALR	Annual Leakage Rate (% of Refrigerant Charge)
EOL	End of Life Emissions (% of Refrigerant Charge)
AEC	Annual Energy Consumption (kWh)
EM	CO_2 produced/kWh (kg CO_{2e}/kWh)
m	Mass of Unit/Material (kg)
RM	CO_{2e} Produced/kg of Recycled Material (kg CO_{2e}/kg)
m_r	Mass of Recycled Material (kg)
RFM	Refrigerant Manufacturing Emissions (kg CO_{2e}/kg)
RFD	CO_{2e} Produced/kg of Refrigerant Recycled (kg CO_{2e}/kg)
MM	CO_{2e} Produced/kg of Material (kg CO_{2e}/kg)
$\dot{Q}$	Heat transfer rate (kW)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}_E$	Evaporator capacity (kW)
$\dot{W}_{Comp}$	Compressor work (kW)
$\dot{Q}_C$	Condenser capacity (kW)
COP	Coefficient of Performance

Greek symbols

η	Efficiency

Subscripts

C	Condenser
Comp	Compressor
E	Evaporator
1, 2, 3,.	State point