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Numerical analysis of using R449A refrigerant alternative to R404A in cooling systems: 3E-analysis (energetic, exergetic, and environmental)

Soğutma sistemlerinde R404A'ya alternatif R449A soğutucu akışkan kullanımının sayısal analizi: 3E-analizi (enerjetik, ekserjetik ve çevresel)

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Numerical Analysis of Using R449A Refrigerant Alternative to R404A in Cooling Systems: 3E-Analysis (Energetic, Exergetic, and Environmental)

Highlights

- *Performance analysis of a single-stage vapor compression cooling system*
- *Analysis of energy, exergy, and environmental impact of R449A, R404A refrigerants*
- *The mass flow rate of R449A is approximately 13% lower than that of R404A, its exergy efficiency is 5% higher.*
- *R449A was found to be approximately 5% lower than R404A in life cycle climate performance analysis.*

Graphical Abstract

In this study, the energy, exergy, and life cycle climate performance of R449A, an alternative to R404A refrigerant, were investigated theoretically

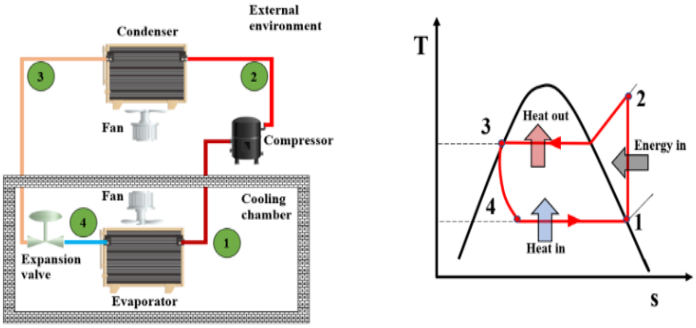

Figure. Single-stage vapor compression cooling cycle and T-s diagram

Aim

To identify the advantages of using R449A instead of R404A refrigerant in cooling systems

Design & Methodology

In a single-stage vapor compression cooling system; the energy, exergy and environmental impact analysis of using R449A refrigerant as an alternative to R404A refrigerant has been theoretically investigated. In the energy analysis of the cooling system; mass flow rates of refrigerants, compressor energy consumption, cooling capacities, cooling effects for cooling mode were investigated

Originality

It is very important to search for new generation refrigerants with lower GWP to be used in the same areas as an alternative to R404A. Due to the lack of a sufficient number of studies in the literature, it is thought that this study will contribute to the researchers and the literature.

Bulgular (Findings)

The mass flow rate of R449A is approximately 13% lower than that of R404A. Compressor energy consumption and cooling capacity of R449A are 2% and 7% higher than that of R404A. The cooling effect of R449A is 23% higher than that of R404A. R449A has an average of 5% higher COP than R404A. The total exergy destruction of R449A is lower than that of R404A. Therefore, the exergy efficiency of R449A is higher than that of R404A. The LCCP of R449A is approximately 5% lower than R404A.

Conclusion

According to the energy, exergy, and environmental analysis results, R449A refrigerant can be used as an alternative refrigerant to R404A in cooling systems

Declaration of Ethical Standards

The author(s) of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Numerical Analysis of Using R449A Refrigerant Alternative to R404A in Cooling Systems: 3E-Analysis (Energetic, Exergetic, and Environmental)

Araştırma Makalesi / Research Article

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ABSTRACT

The direct impact of refrigerants on the environment is largely dependent on the magnitude of global warming potential (GWP) values. In this regard, fluids with low GWP are very important for the environment. Commercial refrigeration accounts for about a third of the world's HFC use. R404A is a derived HFC near an azeotropic mixture. The refrigerant of R404A is widely used in commercial refrigeration systems, especially in supermarkets. As a result of the use of R404A in cooling systems with high GWP, both indirect and direct negative effects on the environment increase. In this study, the energy, exergy, and Life Cycle Climate Performance (LCCP) of R449A, which has a lower GWP value, which can be an alternative to R404A refrigerant, were investigated theoretically. Different evaporator temperatures (-30^{o}C to -5^{o}C) and a condenser temperature (30^{o}C) were used in the analysis. According to the results obtained, while the mass flow rate of R449A is approximately 13% lower than that of R404A, its exergy efficiency is 5% higher. R449A was found to be approximately 5% lower than R404A in LCCP analysis.

Keywords: Global warming, R449A, R404A, energy, exergy, LCCP.

Soğutma Sistemlerinde R404A'ya Alternatif R449A Soğutucu Akışkan Kullanımının Sayısal Analizi: 3E-Analizi (Enerjetik, Ekserjetik ve Çevresel)

ÖZ

Soğutucu akışkanların çevre üzerindeki doğrudan etkisi, büyük ölçüde küresel ısınma potansiyeli (GWP) değerlerinin büyüklüğüne bağlıdır. Bu bakımdan GWP değeri düşük akışkanlar çevre için oldukça önemlidir. Ticari soğutma, dünyadaki HFC kullanımının yaklaşık üçte birini oluşturmaktadır. R404A, azeotropik bir karışımın yakınında türetilmiş bir HFC'dir. R404A'nın soğutucu akışkanı, ticari soğutma sistemlerinde, özellikle süpermarketlerde yaygın olarak kullanılmaktadır. R404A'nın yüksek GWP'li soğutma sistemlerinde kullanılması sonucunda çevreye hem dolaylı hem de doğrudan olumsuz etkiler artmaktadır. Bu çalışmada, R404A soğutucu akışkanına alternatif olabilecek daha düşük GWP değerine sahip R449A'nın enerji, ekserji ve Yaşam Döngüsü İklim Performansı (LCCP) teorik olarak incelenmiştir. Analizde farklı evaporatör sıcaklıkları (-30^{o}C ile -5^{o}C) ve kondenser sıcaklığı (30^{o}C) kullanılmıştır. Elde edilen sonuçlara göre R449A'nın kütle akış hızı R404A'ya göre yaklaşık %13 daha düşük iken ekserji verimi %5 daha yüksektir. LCCP analizinde R449A, R404A'dan yaklaşık %5 daha düşük bulunmuştur.

Anahtar Kelimeler: Küresel ısınma, R449A, R404A, enerji, ekserji, LCCP.

1. INTRODUCTION

The increase in the average global temperature of our world causes climate change. In recent years, the main environmental goals have been to reduce carbon emissions and the impact of global warming. Cooling systems and the refrigerants used play an important role in the increase of greenhouse gases [1,2]. Conventional refrigerants are known to have a high Ozone Depletion Potential (ODP) and destroy the ozone layer when released into the atmosphere.

When the harmful effects of refrigerants on the world emerged as a result of scientific studies, some changes began in their use. Within these changes, different agreements were made between countries in certain periods [3,4]. The production of refrigerants containing harmful substances for the environment, including chlorine and bromine, was controlled by the Montreal Protocol signed in 1987. Thus, a new era has been entered and the search for alternative refrigerants that will cause minimal and/or no harm to the environment has begun. In 1996, the production of Chlorofluorocarbon (CFC) type fluids was completely stopped. By 1989, alternative fluids were developed by finding hydrofluorocarbon (HFC) origin R134a and R123 refrigerants that do not

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harm the ozone layer [5,6]. The Kyoto Protocol was signed in 1997. The Fluorinated Gases Regulation, which was prepared to keep the fluorinated greenhouse gas emissions under control and published by the European Union in 2006 and revised in 2014, entered into force on 1 January 2015. After these agreements, it is of great importance that refrigerants with zero ODP and low GWP, with environmental properties, can be used today and in the future [7,8].

In the selection of alternative refrigerants, besides ODP and GWP, reasonable price range, resistance to pressure and temperatures, appropriate heat transfer coefficient and viscosity are also important [6]. Supermarkets generally use commercial refrigeration systems to keep food under certain conditions. The commercial refrigeration sector accounts for approximately forty percent of HFC use in the refrigeration and air conditioning sector [9,10].

R404A is extensively used refrigerant in commercial refrigeration systems. R404A consists of an azeotropic mixture of R143a /R125/R134a. It has a GWP of 3922 with zero ODP. Various refrigerants are being developed, which are obtained by mixing HFC and Hydrofluoroolefins (HFO) in a certain ratio. One of the different refrigerants that can be used as an alternative to R404A is R449A. R449A is a mixture of HFO/HFC and is used to replace R404A and R507 in refrigeration systems. It has a GWP of 1397 with zero ODP. There is still little data on the benefits of using R449A instead of R404A in refrigeration systems. R449A is a non-toxic-flammable mixture of R32/R125/R134a/R1234yf and was developed for use in refrigeration systems. It is in the A1 class. The basic properties of R404A and R449A were taken from the Refprop program and given in Table 1[9,11-13]. In recent years, as we have seen the effects of climate change, a lot of research has been started to develop environmentally friendly refrigerants in systems.

Mendoza-Miranda et al. (2016) investigated the effects of R448A and R450A working fluids, which can be used instead of R404A and R134a in the micro-fin evaporator model, in cooling systems. The accuracy of the created model was compared by testing it with experimental studies under different operating conditions. As a result, they stated that R450A and R404A refrigerants are more suitable [14].

Li (2017) evaluated the performance of R452A, which can be used instead of R404A. It was stated that R452A keeps emission reductions between 5 and 15% at low and medium evaporation temperatures as to R404A [15].

Cardoso et al. (2017) investigated the performance of alternative refrigerants that can replace R404A in terms of energy efficiency and to reduce the environmental impact of fluorinated gases. It has been determined that R407H and R454A may be superior alternatives in the extended run with a 15% and 9% increase in COP values, respectively, compared to R404A [16]. Llopis et al (2019) studied the energy performance of R454C, R459B, R457A, and R455A refrigerants with lower GWP, as an alternative to R404A. When R454C, R459B, R457A, R455A were evaluated compared to R404, their energy consumption decreased by 2.45%, 11.55%, 10.69%, and 2.9%, respectively [17].

Heredia-Aricapa et al. (2020) examined the mixed refrigerants with low GWP to replace R404A. According to the study, it was stated that R404A should be replaced urgently, and fluids such as R448A, R449A, R454C, R455A, R442A, R407H, and R452A would be good alternatives [18].

Kosan et al. (2020) designed and tested two different industrial systems, classical and micro-channel condenser, using R449a refrigerant. The average COP values were found to be 2.351 for the microchannel model and 2.086 for the classical model. The average exergy efficiency values of the classical and microchannel models were calculated as 23.95% and 25.56%, respectively [19].

Jacob et al. (2020) compared the heat transfer coefficient, pressure drop and lower GWP of R404A with those of R448A and R452A for a system with 1KW cooling capacity and a single 4.7mm tube condenser. In terms of heat transfer coefficient, R448A is higher than R452A. R448A and R452A pressure drops are greater than R404A under same conditions [20].

Saengsikhiao et al.(2020) evaluated the performance of R463A on the system using R404A. It was found that the boiling point of R463A was 23% superior to that of R404A, with a higher cooling capacity and 63% less GWP than that of R404A. The COP value of the R463A alternative refrigerant at low temperatures is 10% higher than that of R404A [21].

Roy and Mandal (2020) conducted an energetic, exergetic, economic, and environmental analysis of a cascade cooling system with 50 kW cooling capacity using pair of R41-R404A, R170-R404A, R41-R161 R170-R161. It was determined that the COP and exergetic efficiency were the highest in the R41-R16, and then in the R170-R161 pair under equal operating conditions. Compared to the R41-R404A, the energy efficiency of the R41-R161 and R170-R161 gave greater results [22].

Oruç and Devecioğlu (2021) compared the performance of R454A and R454C fluids with lower GWP as an alternative to R404A. Different evaporation temperature (-5, 0.5) and different condenser temperature (30,40,50) were used in the study. Compared to R404A, the measured compressor power consumption of R454A and R454C at all condenser temperatures was reduced by 6% and 15%, respectively. When the COP values of R454A and R454C compared to R404A were examined, it was observed that they were 14% and 10% higher, respectively [23].

Yıldırım et al (2021) examined the energy and environmental analysis of R454C fluid, which can be an alternative to R404A. They stated that the COP value of R454C was approximately 4% higher than R404A, and the LCCP value was lower [24].

Table1. Properties of R404A and R449A

Refrigerant	R404A	R449A
Composition	R143a / R125 /R134a (% 44 / % 52 / % 4)	R32 /R125/R134a/R1234yf (%24 / %25 / %26 / %25)
ODP	0	0
GWP	3922	1282
Critical temperature (ºC)	345.20	357
Critical pressure (kPa)	3728.85	4662
Boiling point (ºC)	226.7	227.2
Liquid density (kg/m^3) at 0 ºC	1150.59	1198
Vapor density (kg/m^3) at 0 ºC	30.32	22.43
Liquid C_p (kJ/kg ºC) at 0 ºC	1.39	1.417
Vapor C_p (kJ/kg ºC) at 0 ºC	1	0.976
Liquid heat transmission coefficient (W/m ºC) at 0 ºC	73.15	91.83
Vapor heat transmission coefficient (W/m ºC) at 0 ºC	12.82	12.03
Liquid viscosity (Pa s) at 0 ºC	179.7	190.5
Vapor viscosity (Pa s) at 0 ºC	11	11.29
Safety classification	A1	A1

There are many studies on new generation refrigerants in the literature. However, there is not much research on R449A refrigerant, which can be an alternative to R404A. R404A refrigerant is widely used, especially in commercial refrigeration (supermarket) applications.

For this reason, it is very important to search for new generation refrigerants with lower GWP to be used in the same areas as an alternative to R404A. R449A is designed for use in commercial and industrial low and medium temperature applications by direct evaporation. R449A has approximately 65% lower GWP compared to R404A. In this study, the energy, exergy, and Life cycle climate performance (LCCP) analyses of R449A, which can be an alternative to R404A in commercial cooling systems, were examined. Due to the lack of a sufficient number of studies in the literature, it is thought that this study will contribute to the researchers and the literature.

2. METOD

In this study, energy, exergy, LCCP analyses of R449A refrigerants, a mixture of R32/R125/R134a/R1234yf, which can be an alternative to R404A and have a lower GWP ratio, were examined theoretically. In the study, a single stage refrigeration cycle with vapor compression was theoretically investigated. The diagram of the refrigeration cycle and the related T-s diagram are shown in Fig. 1. It has been assumed that the system consisting of compressor, condenser, expansion valve and evaporator operates in steady state conditions, heat and pressure losses were neglected and there was continuous open flow in the cycle elements.

2.1. Energy and Exergy Analysis [25-29]

The energy and exergy analysis for the system is given in Fig. 1. Compressor compression ratio (CR) is the pressure ratio between the suction line and the discharge line of the cooling system. The cooling capacity of the refrigerants ($\dot{Q}_{evap}$) depends on evaporator enthalpy difference (h_1-h_4)(cooling effect) and refrigerant flow rate ($\dot{m}_r$). The cooling performance coefficient (COP) of the cooling system depends on the cooling capacity and the energy consumption ($\dot{W}_{comp}$) of the compressor.

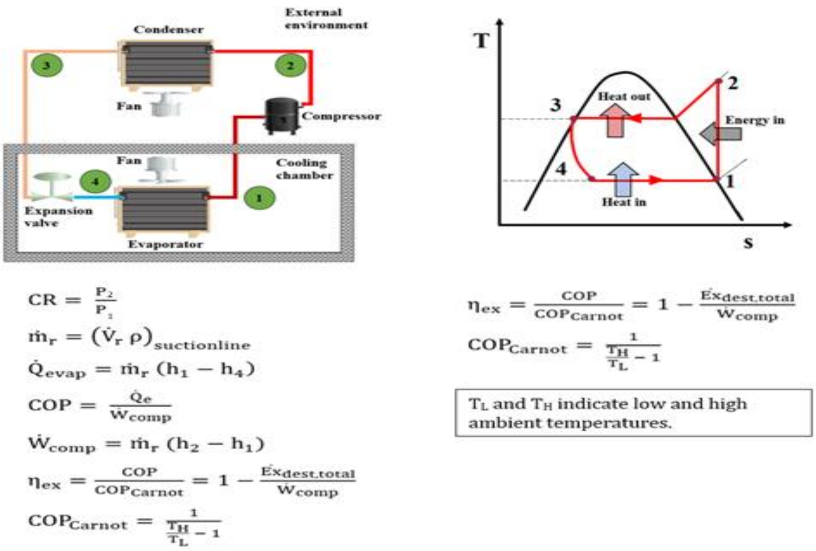

Fig. 1. Schematic view and T-s diagram of a single-stage vapor compression refrigeration cycle

The following assumptions were used in the calculations:

- Evaporator Temperature: -30 °C and -5 °C
- Condenser Temperature: 30 °C
- Compressor isentropic efficiency: 0.8
- The temperature of superheating: 5 °C
- The temperature of subcooling: 5 °C
- The swept volume of compressor: 17.39 cm^3/rev.

Exergy analysis uses the second law of thermodynamics to provide useful information for evaluating, designing, and optimizing the performance of systems in detail. In Fig. 1., η_{ex} is the exergy efficiency and $\dot{E}x_{dest,total}$ is the exergy destruction rate.

2.2. Life cycle climate performance (LCCP)

In the literature, LCCP is discussed in two parts as direct and indirect emissions. Direct emissions consist of the effects of refrigerant released into the atmosphere during the lifetime of the unit. Indirect emissions include emissions from using the unit over its lifetime. It is known that approximately 80-95% of the LCCP emissions of the vapor compression systems used in the study consist of indirect emissions. A large part of the indirect emissions is due to energy consumption [30, 31]. Equation 1 was used to calculate emissions from energy consumption in the LCCP analysis [25, 29]. Turkey's electricity production (2018) consists of 37.3% coal, 29.8% natural gas, 19.8% hydraulic energy, 6.6% wind, 2.6% solar, 2.5% was obtained from geothermal energy, and 1.4% from other sources. According to these data, Turkey's average electricity generation emission (EM) value is calculated as 0.507991 kgCO_2/kWh [30].

$$LCCP = L\ x\ AEC\ x\ EM \qquad (1)$$

The following assumptions were used in the LCCP analyses:

- Cooling capacity ($\dot{Q}_{evap}$): 1 kW
- Device life (L): 10 year

3. RESULTS AND DISCUSSION

In this study, in a single-stage vapor compression cooling system; the energy, exergy and environmental impact analysis of using R449A refrigerant as an alternative to R404A refrigerant has been theoretically investigated. In the energy analysis of the cooling system; mass flow rates of refrigerants, compressor energy consumption, cooling capacities, cooling effects (evaporator enthalpy difference), and coefficients of performance (COP) for cooling mode were investigated. In the case of using R404A and R449A in the cooling system, the variation of the flow rates of the refrigerants according to the evaporator temperature is given in Fig. 2. The flow rate of R404A varies between 9.24 g s^{-1} and 22.08 g s^{-1}, while that of R449A varies between 7.82 g s^{-1} and 19.38 g s^{-1}. It is seen in Fig. 2 that the flow rate of R404A is higher than R449A (about 13%). This is because the suction line density of R404A is higher than R449A. The flow rate of both refrigerants increases as the evaporator temperature increases.

The changes in the compressor energy consumption of R404A and R449A refrigerants according to the evaporator temperature are given in Fig. 3. The compressor energy consumption of R404A ranges from 549.28 W to 576.62 W, while the compressor energy consumption of R449A ranges from 463.47 W to 589.05 W. The compressor energy consumption of R404A is approximately 2% lower than that of R449A.

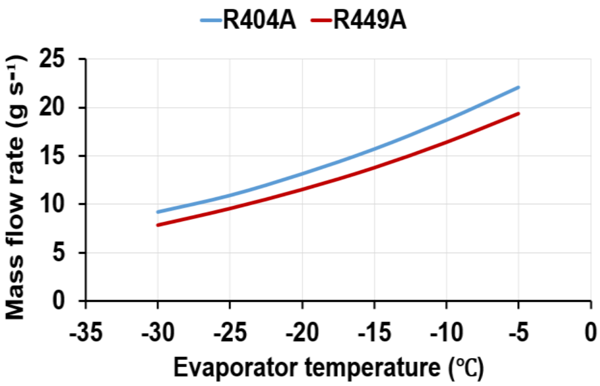

Fig. 2. Mass flow rate for R404A, R449A

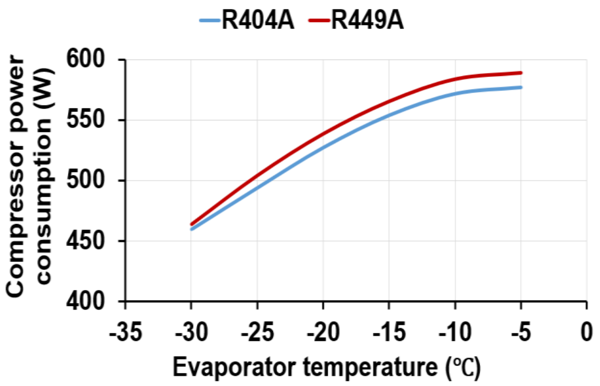

Fig. 3. Compressor energy consumption for R404A, R449A

The cooling capacity depends on the mass flow rate of the refrigerant and the cooling effect (evaporator enthalpy difference). The variation of the cooling capacities of the refrigerants for different evaporator temperatures is shown in Fig. 4. The cooling capacity of R404A ranges from 1078.71 W to 2908.92 W. The cooling capacity of R449A ranges from 1144.21 W to 3091.38 W. Although the refrigerant mass flow rate of R404A is higher than R449A, the cooling capacity of R404A is lower than R449A (approximately 7%). This is because, as seen in Fig. 5, the cooling effect (evaporator enthalpy difference) of R404A is lower than that of R449A (approximately 23%).

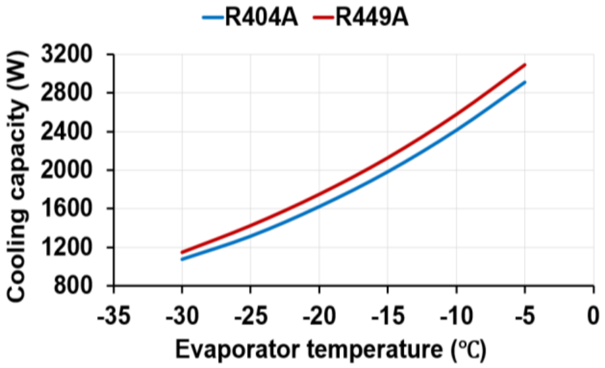

Fig. 4. Cooling capacity for R404A, R449A

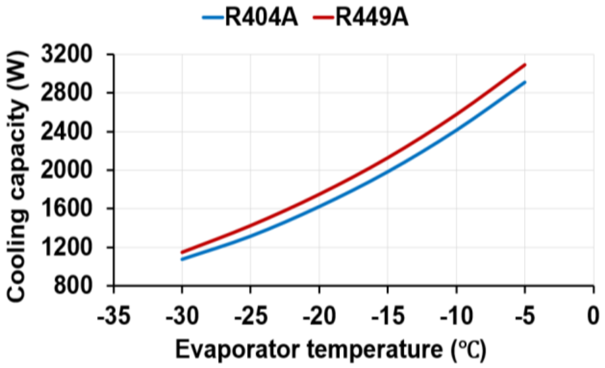

Fig. 5. Refrigerating effect for R404A, R449A

In the case of using R404A and R449A in the cooling system, the variation of COP values depending on the evaporator temperatures is given in Fig. 6. The COP of R404A is between 2.35 and 5.04; for R449A, it varies between 2.47 and 5.25. As seen in Fig. 6, the COP of R449A is approximately 5% higher than R404A. This is because the cooling capacity of R449A is higher than R404A.

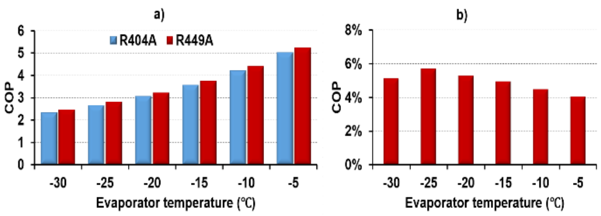

Figure 6. R404A and R449A COP values (a) and comparison (b)

The total exergy efficiency and total exergy destruction are given in Fig.7 and Fig. 8, respectively. The exergy destruction of R404A is between 193.10 W and 196.93 W; The exergy efficiency varies between 0.58 and 0.66. The exergy destruction of R449A is between 181.13 W and 185.56 W; The exergy efficiency varies between 0.61 and 0.68. As seen in Fig. 8, the exergy efficiency of R449A is higher than R404A (average 5%). This is because the exergy destruction rate of R449A is lower than that of R404A (Fig. 8) (approximately 6%).

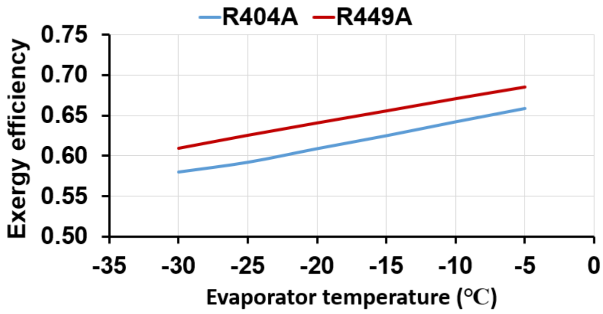

Fig. 7. Total exergy efficiency for R404A, R449A

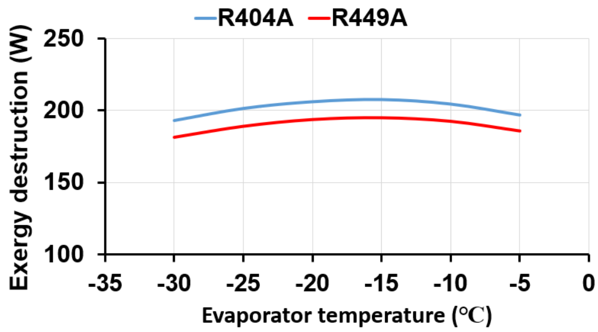

Fig. 8. Total exergy destruction

LCCP analysis of refrigerants is given in Fig. 9. The LCCP value of R404A varies between 19842 kgCO2 and 9238 kgCO2, while the LCCP value of R449A varies between 18877 kgCO2 and 8880 kgCO2. The LCCP value of both refrigerants decreases as the evaporator temperature increases. Because as the evaporator temperature increases, the COP value increases, and therefore the compressor energy consumption decreases. The LCCP of R449A is approximately 5% lower than R404A.

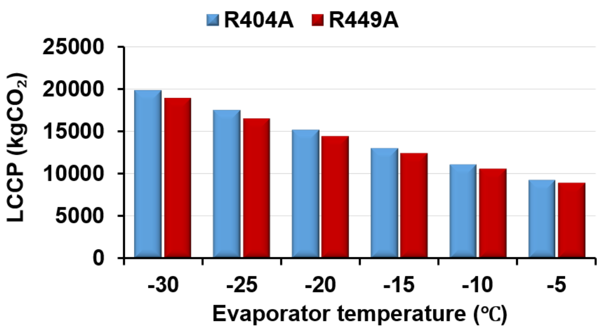

Fig. 9. LCCP of the cooling system

4. CONCLUSION

In this study, energy, exergy, and environmental analysis of the use of R404A and its alternative R449A refrigerants with a low GWP ratio in the refrigeration system were carried out. The main results from the study are given below:

- The mass flow rate of R449A is approximately 13% lower than that of R404A.

- Compressor energy consumption and cooling capacity of R449A are 2% and 7% higher than that of R404A, respectively.
- The cooling effect (evaporator enthalpy difference) of R449A is 23% higher than that of R404A.
- R449A has an average of 5% higher COP than R404A.
- The total exergy destruction of R449A is lower than that of R404A. Therefore, the exergy efficiency of R449A is higher than that of R404A (approximately 5%).
- The LCCP of R449A is approximately 5% lower than R404A.

According to the energy, exergy, and environmental analysis results, R449A refrigerant can be used as an alternative refrigerant to R404A in cooling systems.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Ragıp YILDIRIM: Conceptualization, methodology, investigation, visualization

Kazım KUMAŞ: Conceptualization, methodology

Ali AKYÜZ: Conceptualization, writing - review & editing

Afşin GÜNGÖR: Supervision, reviewing, and editing of the manuscript

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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