Süleyman Demirel Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
Cilt 25, Sayı 2, 245-254, 2021

Süleyman Demirel University
Journal of Natural and Applied Sciences
Volume 25, Issue 2, 245-254, 2021

DOI: 10.19113/sdufenbed.809119

Exergetic Performance Analysis of HFO Based Refrigerants

Mehmet ALTINKAYNAK *1

[1]Isparta University of Applied Sciences, Faculty of Technology, Department of Mechanical Engineering, 32300, Isparta, Turkey

(Alınış / Received: 12.10.2020, Kabul / Accepted: 16.03.2021, Online Yayınlanma / Published Online: 15.08.2021)

Keywords
Refrigerants,
COP,
R452A,
R454C,
R455A,
HFO(Hydrofluoroolefin)

Abstract: GWP (Global Warming Potential) and ODP (Ozone Depletion Potential) occupy an important place in global warming. This has led to the use of refrigerants with low GWP and ODP in cooling systems. Commonly used in cooling systems, R404A refrigerant has a very high GWP value despite having zero ODP. In this study, the exergetic performance analyses of the refrigerants, which may be alternative to R404A, in a theoretical cooling cycle were given comparatively. As an alternative to R404A refrigerant, R452A, R455A and R454C fluids are examined comparatively. COP and exergy destruction, for each refrigerant were examined separately and results were graphically analyzed. COP values of HFO group refrigerants were found as 2.472, 2.312, 2.632, 2.309 for R404A, R452A, R455A and R454C, respectively. In terms of exergy efficiency of HFO group refrigerants were found as 41.5%, 38.8%, 43.9%, 38.7% for R404A, R452A, R455A and R454C, respectively. As a result, thermodynamic properties, GWP and ODP values, energetic and external perspective; As an alternative to the R404A fluid, the best fluid selected is R455A, then R452A and R454C, respectively. The best choice for these alternative refrigerants in cooling systems is R455A.

HFO Bazlı Soğutucu Akışkanların Ekserjetik Performans Analizi

Anahtar Kelimeler
Soğutucu Akışkanlar,
COP,
R452A,
R454C,
R455A,
HFO(Hidrofloroolefin)

Özet: GWP ve ODP, küresel ısınmada önemli bir yer tutmaktadır. Bu, soğutma sistemlerinde düşük GWP ve ODP'ye sahip soğutucuların kullanılmasına yol açmıştır. Yaygın olarak soğutma sistemlerinde kullanılan R404A soğutucu, sıfır ODP'ye sahip olmasına rağmen çok yüksek bir GWP değerine sahiptir. Bu çalışmada teorik bir soğutma çevriminde R404A'ya alternatif olabilecek soğutucu akışkanların ekzerjetik performans analizleri karşılaştırmalı olarak verilmiştir. R404A soğutucu akışkanına alternatif olarak R452A, R455A ve R454C akışkanları karşılaştırmalı olarak incelenir. Her bir soğutucu için COP ve ekserji yıkımı ayrı ayrı incelendi ve sonuçlar grafiksel olarak analiz edildi. HFO grubu soğutucuların COP değerleri R404A, R452A, R455A ve R454C için sırasıyla 2.472, 2.312, 2.632, 2.309 olarak bulundu. HFO grubu soğutucu akışkanların ekserji verimi açısından sırasıyla; R404A, R452A, R455A ve R454C için sırasıyla% 41,5,% 38,8,% 43,9,% 38,7 olarak bulunmuştur. Sonuç olarak termodinamik özellikler, GWP ve ODP değerleri, enerjik ve dış bakış açısı; R404A sıvısına alternatif olarak, seçilen en iyi sıvı sırasıyla R455A, ardından R452A ve R454C'dir. Soğutma sistemlerindeki bu alternatif akışkanlar için en iyi seçim R455A'dır.

1. Introduction

Global warming and the consequent destruction of the ozone layer is a potential danger. The use of GWP and high ODP refrigerants as a factor in the formation of these hazards. In this study, R452A, R454C and R455A mixing fluids, which have low GWP alternatives, are preferred instead of commonly used R404A fluid. The mixing ratios and properties of these fluids are given below.

R452A is a mixture of R125 / R1234yf / R32 with 59% / 30% / 11% mass percentages respectively [1]. Solstice® 452A (R452A) is a zeotropic blend [2], non-ozone-depleting, nonflammable, designed to serve as a lower global-warming-potential (GWP) selection to R-404A and R-507 for low- and medium-temperature implementations in available and novel systems. One of the most feature of Solstice 452A is its matched compressor discharge temperature of R-404A and R-507 at both low- and medium-temperature

*Corresponding author: mehmetaltinkaynak@isparta.edu.tr

circumstances, helping to further minimize application and retrofit costs. In addition, the capacity to approach the R-404A provides the best match and similar energy efficiency [2, 3].

R454C is a mixture of R1234yf / R32 with 78.5% / 21.5% mass percentages respectively Opteon Developed for use in low and medium temperature cooling applications, the (XL-20) R454C refrigerant has a low GWP (150) [4]. R454C mixing fluid, one of the HFO group refrigerants [5], is one of the ideal fluids instead of R404A in direct expansion applications. Performing close to R404A, R454C refrigerant is a low-cost and suitable fluid for new cooling systems [6].

R455A is a mixture of R1234yf / R32 / R744 with 75.5% / 21.5% / 3% mass percentages respectively [7]. R455A (Solstice L40X) is designed for low, medium and high temperature conditions in new cooling systems [8]. It is a slightly flammable and zeotropic mixture [9]. The R455A, which has an ultra-low GWP, has a 146 GWP [10]. It also provides capacity matching and high energy efficiency close to R-404A. It has longer operating potential than propane or air conditioning refrigerants [8]. The analyzes were performed with the help of EES (Engineering Equation Solver) program [11]. Physical properties of fluids are
given in Table 1.

Table 1. The main characteristics of the tested refrigerants [12, 13]

Refrigerant	R404A	R452A	R454C	R455A
Molar Mass	97.6	103.5	90.8	87.5
Boiling Point (°C)	-46.45	-47	-45.9	-52
Critical Temperature (°C)	72.07	75.1	82.4	85.6
Critical Density (kg/m3)	484.5	506.66	999.5	1128.8
Ozone Depletion Potential (ODP)	0	0	0	0
Global Warming Potential (GWP)	3859	1945	146	145
Certainty Class	A1	A1	A2L	A2L

R404A replacements for commercial refrigeration Sethi et al. [14], were made an experimental study. They said that R404A has high GWP value and R448A and R455A the most suitable refrigerants for replacements. R448A matches the capacity with 4 to 8% higher efficiency compared to R404A. R448A resulted from 9% to 20% energy savings for supermarket refrigeration systems. They examined their 24-hour energy consumption in an experiment in which they used R404A as a refrigerant instead of R455A. According to their results, they reveals that using R455A instead of R404A could save 6%. On the other hand Minor et al. [15] stated that the same energy consumption through R404A and R454C in a cooling system.

Li [16], was made a study about life cycle climate performance of transport refrigeration system. He made a comparison R404A and R452A refrigerants. It is seen that, R452A could make lower emission reduction (5-15%) for the food transportation system. He also made comparisons of Pressure-Enthalpy, Temperature-Entropy for R404A and R452A. According to his study R452 A is the most suitable refrigerant instead of R404A and shows a good performance for transport refrigeration systems.

Mota-Babiloni et al. [17], examined R454C and R455A, a mixture refrigerant with low GWP as an alternative to R404A and they have compared COP in vapor compression refrigeration cycles. According to their results, the mixture has a higher COP in the range of 10 to 15% for fluids

Hydroflurocarbons and Hydrofluro-Olefins are mixtures with a maximum combustion rate ≤ 10 cm/s and considered low toxicity cooling fluids, Classified as A2L [18]. Lately the R454C, R455A, R457A and R459B mixtures that have emerged with low GWP are a good R404A alternative refrigerants [19]. Recently, the GWP values of the new mixtures R454C, R455A, R457A and R459B are 146,146,139 and 143, respectively. Instead of R404A, it is a low-class refrigerant with GWP [20].

The Study published by the AHRI revealed dew point-based results in calorimeter tests for R454C [21] and R455A [22] as alternatives to R404A in piston compressors.

Llopis et al [23], their study examined the energy consumptions of mixture fluids at the same cooling load. As a result of the review, they stated that for the fluids R454C, R459B, R457A and R455A there would be a decline in consumption by 2.07%, 10.76%, 10.48% and 2.95% respectively.

Bella et al [24]. In their experimental studies, according to the results of their R455A, R457A and R459B as an alternative to R404A. They applied the conditions of commercial use experimentally in a single stage refrigeration system with hermetic compressor and R-404A. They considered the 24-hour energy consumption values of the fluids in the hermetic compressor refrigeration system. At the end of the experiments, they gave the analysis results of alternative refrigerants.

The novelty of this study is to compare the exergy destruction and COP values of fluids with lower GWP values as an alternative to the R404A refrigerant, which is widely used today.

2. Material and Method

In this study, the performance of R452A, R454C, R455A with low GWP which can be used instead of R404A fluid used in cooling systems has been investigated in the cooling cycle. In the analysis, schematic of refrigeration cycle and parameters shown in Figure 1, Table 2 respectively, were applied to these mixing fluids separately under the same operating conditions.

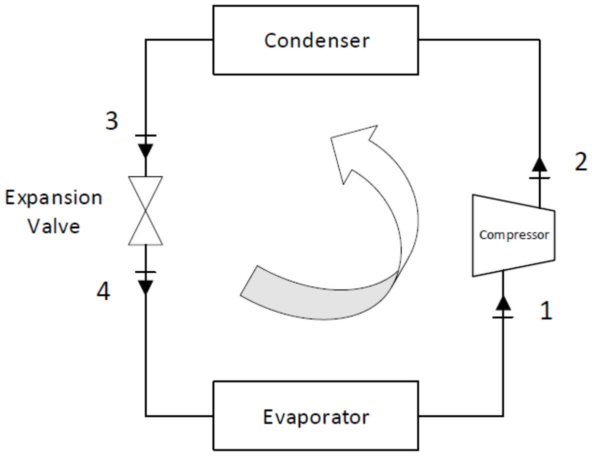

Figure 1. Schematic for the vapor-compression refrigeration cycle

Table 2. Input parameter values assumed in the simulation models.

Parameters	Value
Q_e [kW]	10
Δ_T [°C]	5
T_a [°C]	25
T_c [°C]	45
T_e [°C]	-10
η_{comp} [%]	0,75
Superheating [C]	5

Steam refrigeration cooling cycles commonly used in cooling machines, air conditioning systems and heat pumps consist of four equipment. These are compressor, condenser, expansion valve and evaporator respectively. The steam compression refrigeration cycles are mostly commonly utilized several fields that are heat pumps, refrigeration machines and air conditioning systems. In this cycle, the refrigerant entering the compressor in the saturated vapor phase is pressed into the condenser. The refrigerant, which becomes liquid in the condenser, is passed through the throttle valve and liquid vapor mixture is sent to the evaporator. The liquid vapor phase fluid entering the evaporator from there evaporates by drawing heat from the evaporator. The fluid completing the cycle re-enters the compressor.

Steam refrigeration cooling cycles commonly used in cooling machines, air conditioning systems and heat pumps consist of four equipment. These are compressor, condenser, expansion valve and evaporator respectively. The steam compression refrigeration cycles are mostly commonly utilized several fields that are heat pumps, refrigeration machines and air conditioning systems. In this cycle, the refrigerant entering the compressor in the saturated vapor phase is pressed into the condenser. The refrigerant, which becomes liquid in the condenser, is passed through the throttle valve and liquid vapor mixture is sent to the evaporator. The liquid vapor phase fluid entering the evaporator from there evaporates by drawing heat from the evaporator. The fluid completing the cycle re-enters the compressor.

The thermodynamics models can be described as follows:

The mass flow rate off cycle;

$$\dot{m} = \frac{Q_e}{h_1 - h_4} \quad (1)$$

The compressor input work of cycle;

$$\dot{W}_{comp} = \frac{\dot{m}(h_2 - h_1)}{\eta_{comp}} \quad (2)$$

The energy and exergy balance equations for working fluid compressor, condenser, expansion valve and evaporator can be written below, respectively;

$$\dot{m}h_1 + \dot{W}_{comp} = \dot{m}h_2 \quad (3)$$

$$\dot{m}ex_1 + \dot{W}_{comp} = \dot{m}ex_2 + I_{comp} \quad (4)$$

$$\dot{m}h_2 = \dot{m}h_3 + \dot{Q}_H \quad (5)$$

$$\dot{m}ex_2 = \dot{m}ex_3 + \dot{m}ex_{Q_H} + I_{cond} \quad (6)$$

$$\dot{m}h_3 = \dot{m}h_4 \quad (7)$$

$$\dot{m}ex_3 = \dot{m}ex_4 + I_{\exp\_valve} \quad (8)$$

$$\dot{m}h_4 + \dot{Q}_L = \dot{m}h_1 \quad (9)$$

$$\dot{m}ex_4 + \dot{m}ex_{Q_L} = \dot{m}ex_1 + I_{evap} \quad (10)$$

Exergy of condenser is obtained with;

$$\dot{Q}_{ex,H} = \dot{m}(h_2 - h_3)(1 - \frac{T_0}{T}) \quad (11)$$

Exergy of evaporator is obtained with;

$$\dot{Q}_{ex,L} = \dot{m}(h_1 - h_4)(1 - \frac{T_0}{T}) \quad (12)$$

Cycle energetic and exergetic efficiency are defined as bellow;

$$COP = \frac{Q_e}{W_{comp}} \quad (13)$$

$$\eta_{II} = \frac{COP}{COP_{tr}} \quad (14)$$

$$Ex_1 + W_{comp} = Ex_2 + Ex_{dest,comp} \quad (15)$$

$$Ex_2 = Ex_{QH} + Ex_3 + Ex_{dest,cond} \quad (16)$$

$$Ex_4 = Ex_{QL} + Ex_1 + Ex_{dest,evap} \quad (17)$$

$$Ex_3 = Ex_4 + Ex_{dest,exp,valve} \quad (18)$$

P-h diagrams of fluids according to assumptions and calculations are shown in Figure 2, Figure 3, Figure 4 and Figure 5, respectively.

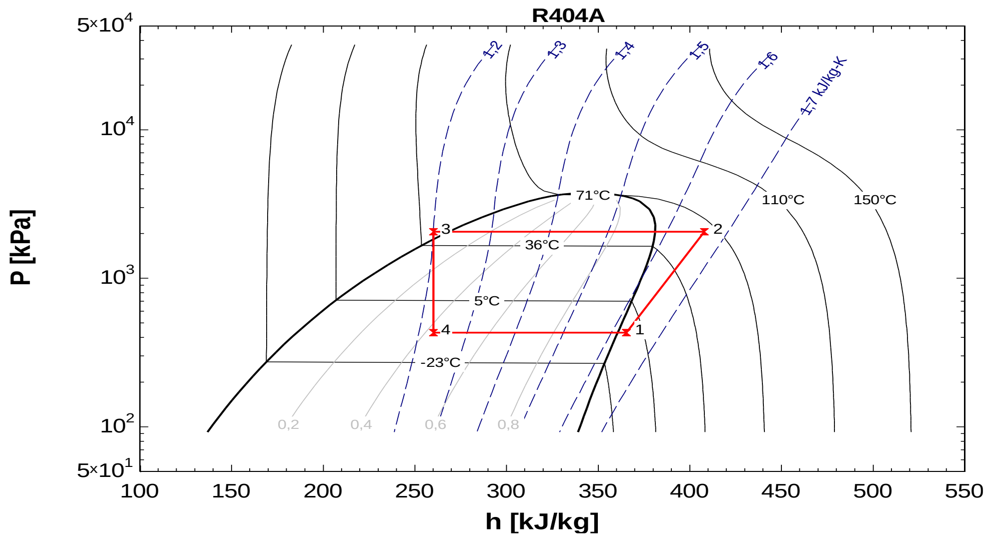

Figure 2. P-h diagram of R404A according to given assumptions

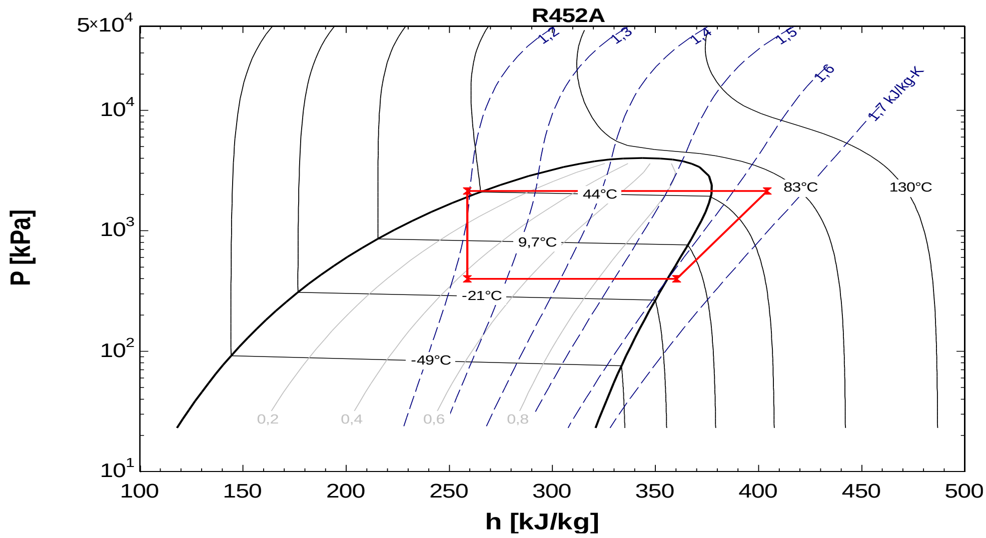

Figure 3. P-h diagram of R452A according to given assumptions

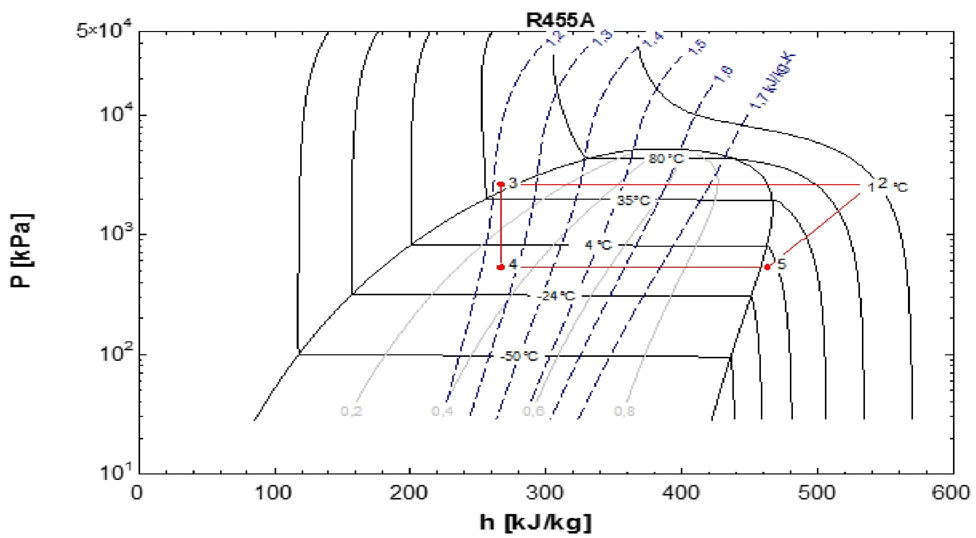

Figure 4. P-h diagram of R455A according to given assumptions

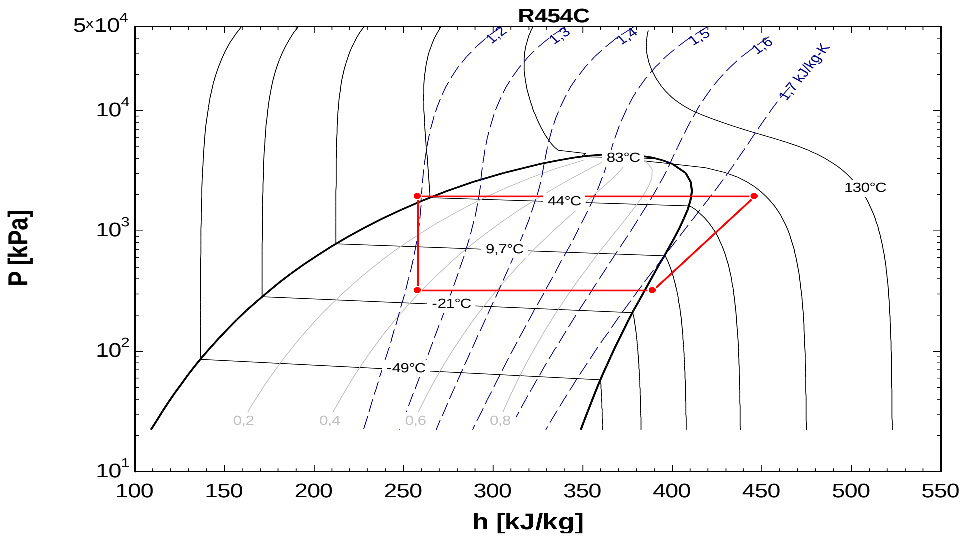

Figure 5. P-h diagram of R454C according to given assumptions

3. Results

COP, exergy destruction and exergy efficiency and values of each element used in the system are presented below. The engineering equation solver (EES) software program has been used for cooling system [11]. Refrigerants, which tested in cooling system, of COP values are illustrated Figure 6. As can see from figure 6 highest COP value is R455A. This fluid is followed by R404A, R452A and R454C, respectively. COP values of HFO group refrigerants were found as 2.472, 2.312, 2.632, 2.309 for R404A, R452A, R455A and R454C, respectively.

The power consumed in the compressor of the refrigerants is given in Figure 7. As shown in Figure. 7, the lowest compressor work is performed by the R455A refrigerant while the highest compressor work is done by R454C refrigerant. While power consumption increased in R452A and R454C refrigerants, savings of 7% were observed in R455A.

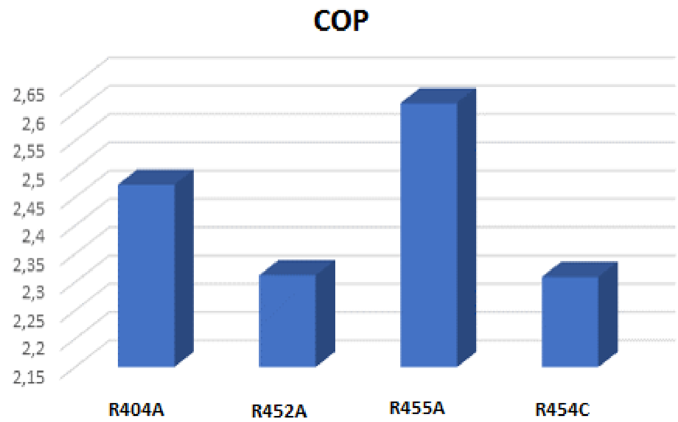

Figure 6. COP values for the system due to using various fluids

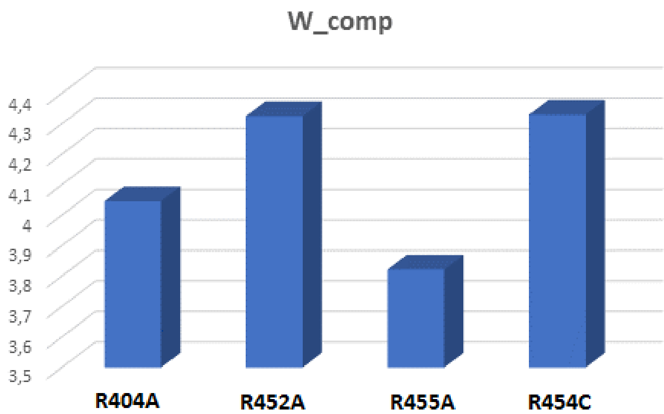

Figure 7. The power consumed in the compressor of the refrigerants

If we investigated COP values for the system, R455 A refrigerant gives the highest value after R404A. Figure 8 shows the exergy destructions of R404A. The lowest exergy destruction is observed in R455A when exergy destructions were examined. Again, the nearest exergy destruction value to R404A was seen in R452A.

When all figures were observed, it was seen that the highest exergy destruction of the refrigerants used in the study was in the compressor. The second biggest exergy destruction was found in the expansion valve for all refrigerants. The external destruction of these components is since they are composed of moving components. The remaining parts have just thermic destruction.

Figure 8 shows the exergy destruction of each component for the cooling cycle using the R404A, depending on the evaporator temperature. Exergy destruction was reduced both compressor and expansion valve because of the increased evaporator temperature. Shown the figure, with the increasing evaporator temperature, the exergy destruction was decreased in the compressor and expansion valve for R404A refrigerant fluid. The reason for the reduction of exergy destruction in the compressor is that the compressor load decreases due to the increase in the evaporator temperature. As the thermal load from the condenser decreases, the exergy destruction in the condenser decreases.

Figures 9, 10, 11 illustrate the graphs of R452A, R455A and R454C. In the graphs, it is seen that R452A and R455A have similar exergy damage. R452A and R455A have been found to have similar properties to R454C, R404A.

Exergy values of fluids used in the study the lowest destruction value is R455A while the highest destruction value in 452A. As a result, R455A has been found to be the most suitable alternative fluid for exergy destruction.

As seen in Figure 9, it is calculated that the temperature change between -10 ° C and 0 ° C in the evaporator for R452A refrigerant decreases by 0.56 kW - 0.18 kW for the evaporator in exergy destruction. The reason for this decrease in exergy destruction is due to the increasing evaporator temperature. As seen in Figure 10, it is calculated that the temperature change between -10 ° C and 0 ° C in the evaporator for R455A refrigerant decreases by 0.46 kW - 0.14 kW for the evaporator in exergy destruction. As seen in Figure 11, it is calculated that the temperature change between -10 ° C and 0 ° C in the evaporator for R454C refrigerant decreases by 0.59 kW - 0.21 kW for the evaporator in exergy destruction.

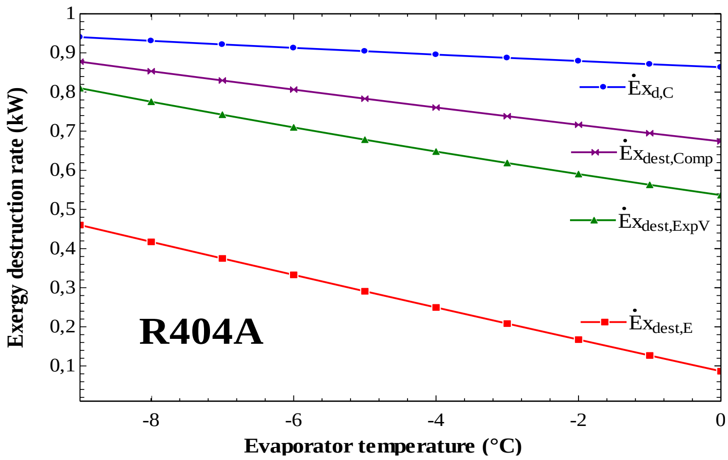

Figure 8. Exergy destruction values for evaporator temperature of the system using R404A

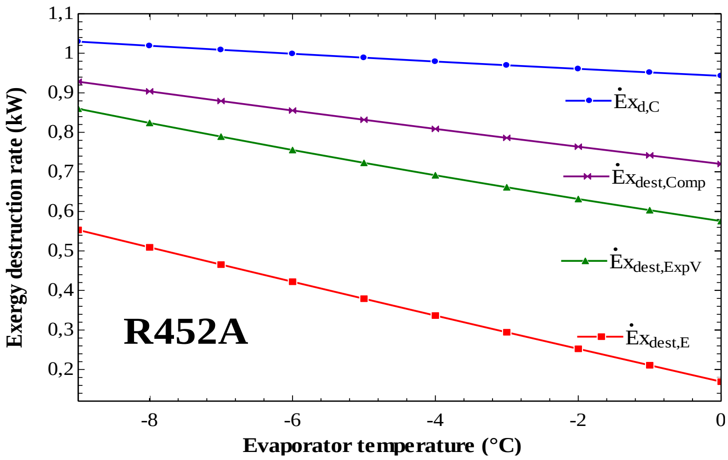

Figure 9. Exergy destruction values for evaporator temperature of the system using R452A

Exergy destruction of refrigerants depending on the condenser temperature is shown in Figure 12,13,14,15. As seen in Figure 12, it is calculated that the temperature change between 25 ° C and 45 ° C in the condenser for R404A refrigerant increases by 0.04 kW - 0.95 kW for the condenser in exergy destruction. Figure 13 shows, it is calculated that the temperature change between 25 ° C and 45 ° C in the condenser for R452A refrigerant increases by 0.09 kW - 1.05 kW for the condenser in exergy destruction. As seen in Figure 14, it is calculated that the temperature change between 25 ° C and 45 ° C in the condenser for R455A refrigerant increases by 0.13 kW - 1.16 kW for the condenser in exergy destruction. As seen in Figure 15, it is calculated that the temperature change between 25 ° C and 45 ° C in the condenser for R454C refrigerant increases by 0.24 kW - 1.19 kW for the condenser in exergy destruction.

The highest exergy destruction is observed at R454C relying on the condenser temperature. the lowest exergy destruction is observed in R452A at condenser temperature.

According to the condenser temperature, the highest exergy destruction in the compressor is observed at R452A though condenser temperature, the lowest exergy destruction in the compressor is observed in R455A.

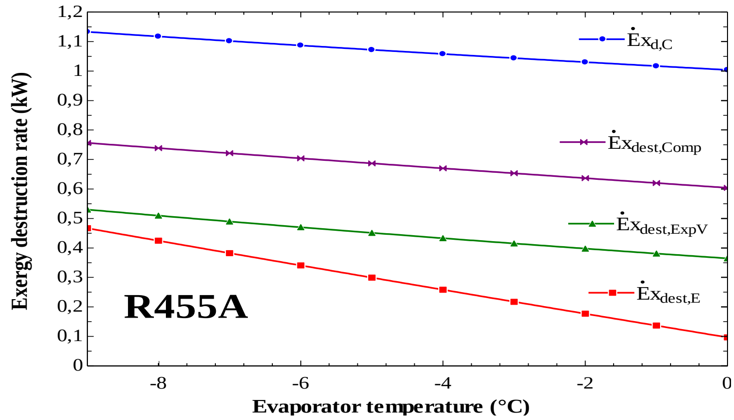

Figure 10. Exergy destruction values for evaporator temperature of the system using R455A

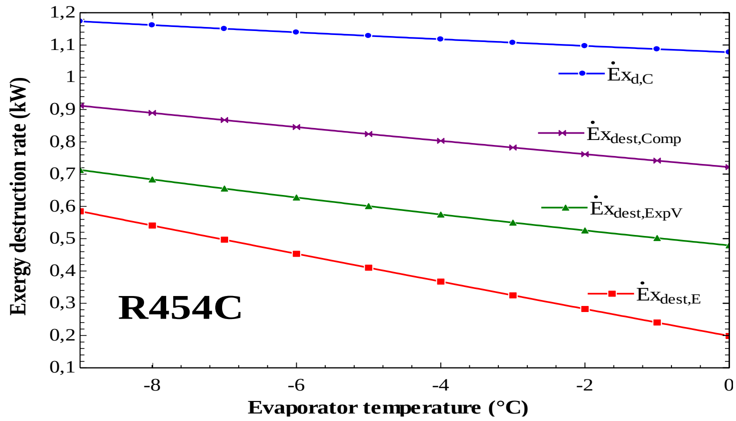

Figure 11. Exergy destruction values for evaporator temperature of the system using R454C

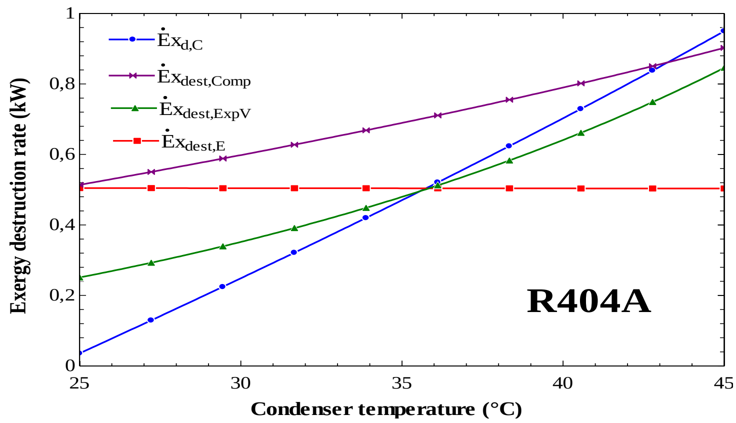

Figure 12. Exergy destruction values for condanser temperature of the system using R404A

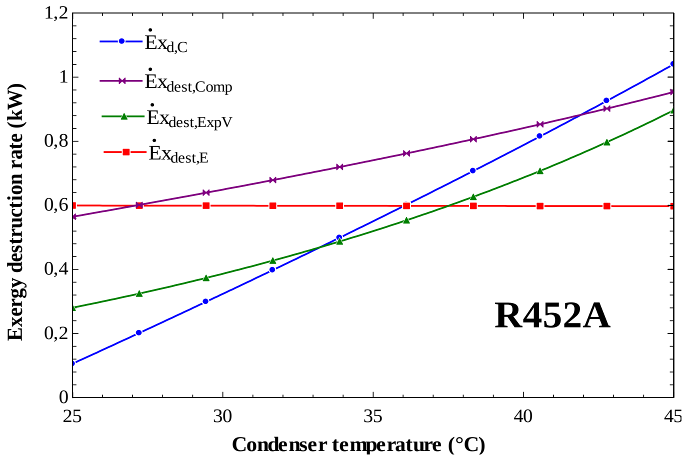

Figure 13. Exergy destruction values for condanser temperature of the system using R452A

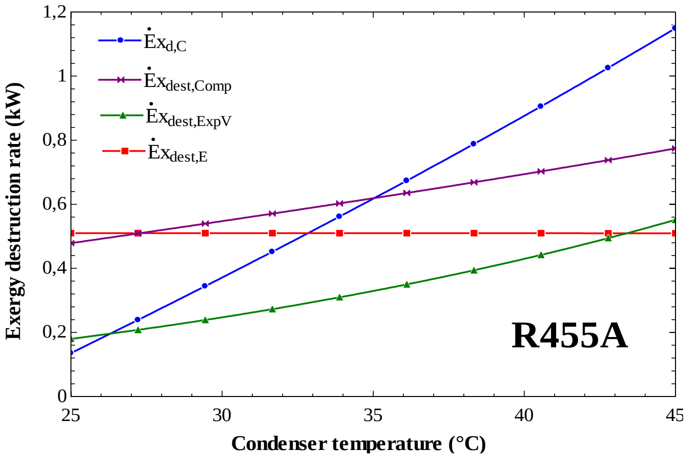

Figure 14. Exergy destruction values for condanser temperature of the system using R455A

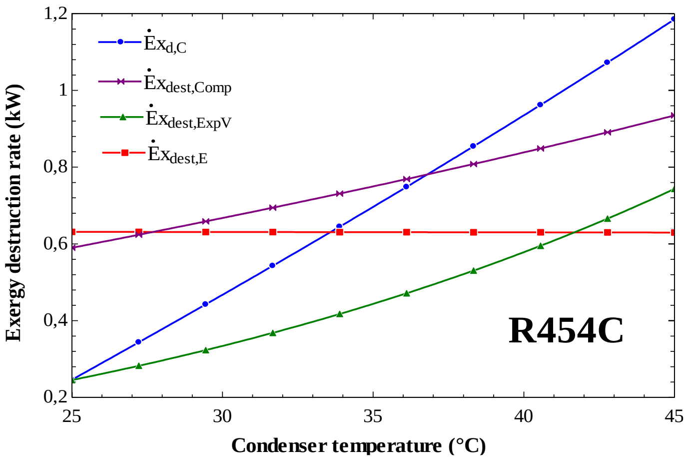

Figure 15. Exergy destruction values for condanser temperature of the system using R454C

4. Discussion and Conclusion

In this article, energy exergy analysis for R452A, R455A and R454C from HFO group fluids which are considered as alternative to R404a were presented comparatively. From these compared fluids, the highest COP value is 2.63 to R455A fluid. The lowest COP value was 2.31 belong to R452A.

COP values of HFO group refrigerants were found as 2.472, 2.312, 2.632, 2.309 for R404A, R452A, R455A and R454C, respectively. It is understood from this that the highest COP value belongs to the refrigerant R455A whereas the lowest COP value was seen at R454C.

In terms of exergy efficiency of HFO group refrigerants were found as 41.5%, 38.8%, 43.9%, 38.7% for R404A, R452A, R455A and R454C, respectively. It is understood from this that the highest exergy efficiency belongs to the refrigerant R455A though the lowest COP value was seen at R454C.

As a result, thermodynamic properties, GWP and ODP values, energetic and external perspective; As an alternative to the R404A fluid, the best fluid selected is R455A, then R452A and R454C, respectively. The best choice for these alternative fluids in cooling systems is R455A.

Considering all these data, R455A, as an alternative fluid, performs better in terms of energy and exergy efficiency in a cooling system.
Use of alternative fluids for the cooling system examined; it can be considered the right choice in terms of system efficiency and energy consumption of the system.

Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" are complied with, and that none of the actions stated under the heading "Actions Against Scientific Research and Publication Ethics" are not carried out.

References

[1] Lillo, G., Mastrullo, R., Mauro, W.A., Viscito, L. (2018). Flow boiling data of R452A. Energy Procedia, 1034-1041.

[2] Honeywell Refrigerants https://www.honeywell-refrigerants.com/europe/product/solstice-452a/ (Access Date:05.01.2020)

[3] American Society of Heating. Refrigerating and Air-Conditioning Engineers, (2013). ASHRAE Standard 34 Designation and Safety Classification of Refrigerants.

[4] Miranda, C. J. M. (2018). Futuro De Los Gases Refrigerantes En Trenes De Renfe Trabajo Fin De Master. Master Universitario En Sistemas Ferroviarios.

[5] Miyara, A. (2018). Developments of Next Generation Refrigerants and Heat Transfer. International Mechanical and Industrial Engineering Conference, 204, Malang, Indonesia, 6-12

[6] Makhnatch, P., Mota-Babiloni, A., Khodabandeh, R., Haro-Ortuno, J. (2018). Characteristics of R454C and R455A as R404A Alternatives in Commercial Refrigeration. 5th IIR Conference on Sustainability and the Cold Chain, Beijing,China. 547-553.

[7] Azzolin M., Berto A., Bortolin S., Del Col D. (2017). Condensation Heat Tranfer of Non-Azeotropic Mixtures Inside Channels. 13th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Portoroz, Slovenia. 152-157.

[8] Honeywell Refrigerants https://www.honeywell-refrigerants.com/europe/product/solstice-l40x (Access Date:05.01.2020)

[9] Azzolin M., Berto A., Bortolin S., Del Col D. (2018). Vaporization of Binary and Ternary Non-Azeotropic Mixtures Inside Channels. 16th International Conference on Heat Transfer, Beijing, China. 1450-1462.

[10] Zgliczynski, M., Sedliak, J. (2018). Thermal Profile Of A Reciprocating Compressor Using Low GWP Refrigerants. 24th International Compressor Engineering Conference. Indiana, USA. 1699-1704.

[11] Klein, S. A. (2011). Engineering Equation Solver, version 9.022-3D, F-Chart Software.

[12] Fchart http://fchart.com/ees/eeshelp/fluid_property_information.htm (Access Date:10.02.2020)

[13] Maknatch, P, Khodabandeh, R. (2015). Evalution of cycle performance of R448A and R449A as R404A replacements in supermarket refrigeration system. Proceedings of the 24th IIR International Congress of Refrigeration, August 16-22 Yokohama, Japan.

[14] Sethi, A. Pottker, G. M. S. Y. (2016). Experimental evaluation and field trial of low global warming potential R404A replacements for commercial refrigeration. Science and Technology for the Built Environment, 22(8), 1175-1184.

[15] Minor, B.H., Shah, S., Simoni, L. (2016). Testing of HFO Refrigerant with Less Than 150 GWP in a Commercial Freezer, 16thInternational Refrigeration and Air Conditioning Conference, Purdue, United States of America. 1729.

[16] Li, G. (2017). Comprehensive investigation of transport refrigeration life cycle climate performance. Sustainable. Energy Technologies and Assessments, 21, 33-49

[17] Babiloni, A. M., Ortuño, J. H., Esbrí, J. N., Cervera, Á. B. (2018). Experimental drop-in replacement of R404A for warm countries using the low GWP mixtures R454C and R455A. International Journal of Refrigeration, 91, 136–145.

[18] American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2016). ANSI/ASHRAE Standard 34, designation and safety classification of refrigerants.

[19] BITZER Kühlsmaschienbau GmbH (https://www.bitzer.de/shared_media/documentation/a-501-19.pdf)

[20] Anta, D. C. (2018). Estudio De Refrigerantes Alternativos Al R404A Para Aplicaciones De

Refrigeración Comercial. Trabajo Final De Grado. Universitat Jaume. Costellon, Valencia.

[21] Sedliak J. (2015). Compressor Calorimeter Test of Refrigerant Blend DR3 in a R-404A Reciprocating Compressor. Air-Conditioning, Heating, and Refrigeration Institute (AHRI) low-gwp alternative refrigerants evaluation program (Low-GWP AREP).

[22] Sedliak J. (2015). Compressor Calorimeter Test of Refrigerant Blend HDR110 in a R-404A Reciprocating Compressor. Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP).

[23] Llopis, R., Anta, D. C., Sánchez, D., Andrés, L. N., Gil, J. C., Cabello, R. (2019). R-454C, R-459B, R-457A and R-455A as low-GWP replacements of R-404A Experimental evaluation and optimization. International Journal of Refrigeration, 106, 133–143.

[24] Bella, B., Pham, H., Rajendran, R. (2018). Sustainable refrigerants for comfort and refrigeration. In: Proceedings of the 1st IIR International Conference on the Application of HFO Refrigerants, Birmingham, UK.