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Original Research Article

# Numerical energy and exergy analysis of cooling systems: low GWP alternative refrigerants (R450A and R1234ze) to R134a

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## ABSTRACT

The use of new generation refrigerants in heating and cooling systems operating according to vapor compression cycles and the preference of renewable energy sources is very important to reduce the negative effects on the environment. Here, the energy and exergy performance of refrigerant R450A and R1234ze, which are alternatives to R134a, were theoretically examined. Energy and exergy analysis of cooling system were performed under the same working conditions (source temperature is between -15 and 15 $^{o}$C, and heat sink temperature is constant 30 $^{o}$C). The COP values of R134a, R1234ze, and R450A were 2.00, 1.98 and 1.97, respectively, while the heat source temperature was -15 $^{o}$C. The heat source temperature was 15 $^{o}$C, the COP values of R134a, R1234ze, and R450A were 4.82, 4.83 and 4.79, respectively. Under the given operating conditions, the highest total exergy destruction occurred at R134a, while the lowest total Exergy destruction occurred at R1234ze. The refrigerant with the highest and lowest cooling capacity was R134a and R1234ze. According to the results obtained from the analysis, it was concluded that R450A and R1234ze can be used instead of R134a.

*Keywords:* Global warming; New generation refrigerants; R134a/R1234ze mixture; Energy and exergy

## 1. Introduction

Energy consumption is increasing every day due to continuous population growth and technological developments in the world. As energy consumption increases, greenhouse gas emissions increase, causing global warming, climate change. Heating and cooling systems operating according to vapour compression cooling cycles are widely used. The energy consumption of vapour compression systems is very large to be underestimated, and these systems account for a significant percentage of greenhouse gas emissions. Direct emissions for vapour compression systems are caused by leaks of refrigerants. Direct emissions account for approximately 20% of vapour compression systems. Indirect emissions of these systems are caused by energy consumption, production of system components, production of refrigerant and recycling of its components. These emissions correspond to 80% [1]. Due to the environmental effects caused by refrigerants, new refrigerants with low GWP (global warming potential) and ODP (ozone depletion potential) values have been sought and new alternatives have been developed in recent years [2-5]. Because of the damage caused to the ozone layer by chlorofluorocarbon (CFC) group refrigerants, such as R12 gas, their use has limited by the Montreal Protocol. R134a, a refrigerant from the hydrofluorocarbon (HFC) group, has been used instead of B12 in vehicles produced since 1990 [6]. However, since R134a has a GWP value of 1300, its use in new vehicles manufactured in European Union countries has been limited since 2017. R1234yf, a refrigerant from the Hydrofluoroolefin (HFO) group developed instead of R134a, is approximately 22 times more expensive than R134a today, although it has a GWP value as low as 4, and its cooling capacity is lower than R134a [7,8].The refrigerants R1234yf and R1234ze, which are in the hydrofluoroolefins (HFO) group, have been developed as an alternative to R134a. It has been proven by various studies that use of R1234yf in the cooling system does not improve energy performance, and the use of R1234ze requires changes in the system [9,10]. In order to eliminate these negative properties of HFOs, various refrigerants obtained by mixing HFC and HFOs with a certain ratio have being developed [11,12]. Of these mixtures, R450A (R134a and R1234ze) are today fireproof HFO/HFC mixtures for medium temperature cooling and air systems. R450A is classified by ASHRAE as a non-toxic and non-flammable refrigerant (A1) group, like R134a. Thanks to zero ODP and low GWP values, the availability of such refrigerants today and in the future is of great importance. The properties of R134a, R1234ze, and R450A are given in Table 1 [13,14].

**Table1.** The properties of R134a, R1234e, and R450A

| **Refrigerants** | **R134a** | **R1234ze** | **R450A** |
|---|---|---|---|
| Compound | Pure | Pure | R134a/R1234ze (42/58) |
| ODP | 0 | 0 | 0 |
| GWP | 1300 | 7 | 547 |
| Critical Temperature [ºC] | 101.10 | 109.36 | 104.47 |
| Critical Presuure [kPa] | 4059.30 | 3634.9 | 3814 |
| Boiling Point[ºC] | -26.07 | -18.95 | -23.36 |
| Liquid Density*[kg/m$^3$] | 1295.3 | 1240.2 | 1252.8 |
| Vapou Density [kg/m$^3$] | 14.35 | 11.72 | 13.99 |
| $C_p$* (liquid) [kJ/kg ºC] | 1.34 | 1.30 | 1.32 |
| $C_p$* (Presuure) [kJ/kg ºC] | 0.89 | 0.88 | 0.90 |
| Thermal Conductivity (liquid)*[W/m ºC] | 92.01 | 83.21 | 83.02 |
| Thermal Conductivity (vapour) *[W/m ºC] | 11.50 | 11.57 | 11.58 |
| Viscosity (liquid)*[Pa s] | 266.53 | 269.09 | 257.74 |
| Viscosity (vapour)*[Pa s] | 10.72 | 11.19 | 11.16 |
| **Safety Classification** | A1 | A2L | A1 |

*0 ºC

In recent years, the literature has included various studies on the thermodynamic performance of refrigerants. Vaghela (2017) studied the thermodynamic performance of R290, R600a, R407C, R410A, R404A, R152a, and R1234yf as alternatives to replacing R134a in vehicle air conditioning system. According to the analysis, R1234yf is the most suitable alternative refrigerant [15]. Diani et al. (2018) experimentally examined the heat transfer coefficients and pressure changes during condensation of R1234ze and R1234yf in a micro-tube. The study showed that the heat transfer coefficient of R1234ze is close to R134a, while R1234yf has lower values [16]. Bolaji et al. (2019) theoretically studied the energy potential of R430A, R440A, and R450A, which could replace R134a in a vapour compression system. It is concluded that R440A has the optimum performance from the refrigerants [17]. Zhang et al. (2019) experimentally studied the effect of using R1234ze and R1233zd instead of R134a, R245fa on condensation heat transfer and pressure change. R1234ze and R1233zd have higher pressure changes and heat transfer coefficients than refrigerants under the same operating conditions [18]. Gill et al. (2019) concluded that when R450A was preferred instead of R134a, the system total irreversibility with R450A was lower and the exergy efficiency was higher than the R134a system. The evaporator was very high efficient component and that the compressor was the very low efficient component for these refrigerants [19]. Khalil et all. (2016) has built a vapour compression cold chamber in which the performance of high GWP refrigerant R134a and low GWP refrigerant R1234ze was compared. The cooling capacity of r1234ze has been shown to be 2% to 13% lower than R134a. The lowest evaporation temperature for R1234ze was -13 ºC, while the lowest temperature of R134a was -30 ºC. In addition, according to the study, the R1234ze has a power consumption of about 9% to 15% lower than the R134a [20]. Direk and Yüksel (2020) experimentally analyzed the parameters of performance for heat pump systems for R134a and R1234yf. In the study, R134a performed better than the R1234yf for COP, heat capacity and that the air speed [21]. Dikmen et al. (2020) examined the cascade cooling system performance of utilizing new generation refrigerants. In their studies, R454C/R1234ze, R454C/R1234yf, R454C/R717, R744/R290, and R744/R717 pairs with zero ODP and low GWP value were used. In their analysis, they stated that very high COP value was gotten in the R454C/R717 fluid mixture [22]. Agarwal et al (2021), studied the energy and exergy performance of a compression supercooling design. R1234ze is the best alternative refrigerant considered in the analysis and can replace R134a in terms of exergy efficiency for COP and temperatures less than 30℃ [23].

There is not much work on modeling cooling systems of new generation refrigerants with low GWP rate. Preliminary and theoretical knowledge about fluid behavior is needed to analyze the energy performance of such refrigerants. In this work, energy and exergy analysis of the use of new generation refrigerants R450A and R1234ze instead of R134a in cooling systems between wide operating temperatures was carried out. Studies on new generation low GWP refrigerants are very important in terms of industrial applications and their environmental impact and contribution to the literature

## 2. System Description

In this study, a theoretical study of the performance of refrigerant R134a, R1234ze, and R450A was conducted using a single-stage vapor compression cooling system included in Figure 1. The P-h diagram of a cooling cycle is given separately in Figure 1. It has been accepted that there was no pressure loss in the pipes for the cooling system and that all elements were constantly open flow. The admissions are given in Table 2.

## 3. Thermodynamic Analyses

### 3.1. Energy analysis

By the first law of thermodynamics, the change in the performance coefficient of the cooling system (COP) under same operating conditions (evaporator temperature, condenser temperature, compressor isentropic efficiency, super heating temperature and subcooling temperature) can be studied.

### 3.2. Exergy analysis

Exergy analysis uses the second law of thermodynamics to provide useful information for evaluating, designing and optimizing the performance of systems in detail. In the analyses, equalization 6 -17 in Table 4 were used [25, 26].

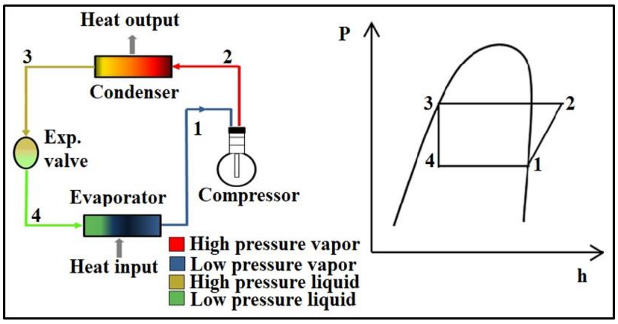


**Fig. 1.** Schematic view of a single stage vapor compression refrigeration cycle and pressure – enthalpy graph

**Table 2.** Assumed values for thermodynamic analyses

| | |
|---|---|
| Heat sink temperature ($T_c$) | 30 ºC |
| Heat source temperature ($T_e$) | From -15 ºC to 15 ºC |
| Isentropic efficiency | 0.70 |
| Super heating temperature | 5ºC |
| Subcooling temperature | 5ºC |
| Compressor sweep volume | 26.11 $cm^3$/rev. |
| Temperature difference between cooling ambient and evaporator | 10 ºC |
| Temperature difference between heat reject and condenser | 10 ºC |
| Dead state temperature ($T_0$) | 25 ºC |
| Dead state Pressure ($P_0$) | 101.325 kPa |

**Table 3.** Energy analysis formulations [24,25]

| | | |
|---|---|---|
| Theoretical mass flow rate | $\dot{m}_r = (\dot{V}_r\,\rho)_{suction,line}$ | (1) |
| Cooling capacity of refrigerants | $\dot{Q}_{evap.} = \dot{m}_r\,(h_1 - h_4)$ | (2) |
| Compressor energy consumption | $\dot{W}_{comp.} = \dot{m}_r\,(h_2 - h_1)$ | (3) |
| Heat released from the condenser | $\dot{Q}_{cond.} = \dot{m}_r\,(h_2 - h_3)$ | (4) |
| The coefficient of performance | $COP = \frac{\dot{Q}_{evap.}}{\dot{W}_{comp.}}$ | (5) |
| $\dot{V}_r$: volumetric flow rate, ρ: Refrigerant density, h: specific enthalpy value of the relevant reference point of the cooling system | | |

## 4. Results and Discussion

The use of refrigerant R450A and R1234ze as an alternative to R134a in cooling systems was theoretically studied. Energy and exergy analysis of refrigerants was performed under the same working conditions.

### 4.1. Energy analysis results

In the energy analysis of the cooling system, the mass flow rates of refrigerants, cooling capacities, compressor energy consumption, COP values and discharge temperatures were examined according to the first law of thermodynamics. The change in mass flow rates of refrigerants at different operating temperatures and the change in cooling capacities are seen in Figure 2. As the temperature of the evaporator increases, the mass flow rate of refrigerants also increases. Under the given operating conditions, the mass flow rate for R134a ranges from 7.02 g $s^{-1}$ to 21.79 g $s^{-1}$, while the mass flow rate for R450A ranges from 6.92 g $s^{-1}$ to 21.36 g $s^{-1}$ and R1234ze's mass flow ranges from 5.65 g $s^{-1}$ to 17.77 g $s^{-1}$. R134a has the highest mass flow rate. Since the absorption line density of R134a is higher than R450A and R1234ze, R134a is seen as having the highest refrigerant flow rate.

**Table 4.** Exergy analysis equations

| | | |
|---|---|---|
| Exergy destruction rate | $\dot{E}x_d = \sum\left(1-\frac{T_0}{T}\right)\dot{Q} - \dot{W}_{in} + \sum_{in}\dot{m}e - \sum_{out}\dot{m}e$ | (6) |
| Specific Exergy | $\psi_i = (h_i - h_0) - T_0(s_i - s_0)$ | (7) |
| For compressor | $\dot{E}x_{d,comp.} = \dot{E}x_{d,1-2} = \dot{W}_{comp.} - \dot{m}_r\,[h_2 - h_1 - T_0(s_2 - s_1)]$ | (8) |
| Exergy efficiency (For compressor) | $\eta_{ex,comp.} = 1 - \frac{\dot{E}x_{d,comp.}}{\dot{W}_{comp.}}$ | (9) |
| For condenser | $\dot{E}x_{d,cond.} = \dot{E}x_{d,2-3} = \dot{m}_r\,[h_2 - h_3 - T_0(s_2 - s_3)] - \dot{Q}_{cond.}\left(1-\frac{T_0}{T_H}\right)$ | (10) |
| Exergy efficiency (For condenser) | $\eta_{ex,cond.} = 1 - \frac{\dot{E}x_{d,cond.}}{\dot{E}x_2 - \dot{E}x_3}$ | (11) |
| For expansion valve | $\dot{E}x_{d,AXV} = \dot{E}x_{d,3-4} = \dot{m}_r\,[h_3 - h_4 - T_0(s_3 - s_4)]$ | (12) |
| Exergy efficiency (For expansion valve ) | $\eta_{ex,AXV} = 1 - \frac{\dot{E}x_{d,AXV}}{\dot{E}x_3 - \dot{E}x_4}$ | (13) |
| Evaporator | $\dot{E}x_{d,evap.} = \dot{E}x_{d,4-1} = \dot{m}_{ref}\,[h_4 - h_1 - T_0(s_4 - s_1)] - \left[-\dot{Q}_{evap.}\left(1-\frac{T_0}{T_L}\right)\right]$ | (14) |
| Evaporator | $\eta_{ex,evap.} = 1 - \frac{\dot{E}x_{d,evap.}}{\dot{E}x_4 - \dot{E}x_1}$ | (15) |
| Cooling system | $\dot{E}x_{d,sistem} = \dot{E}x_{d,comp.} + \dot{E}x_{d,cond.} + \dot{E}x_{d,AXV} + \dot{E}x_{d,evap.}$ | (16) |
| Cooling system | $\eta_{ex,system} = 1 - \frac{\dot{E}x_{d,sistem}}{\dot{W}_{comp.}}$ | (17) |
| $h_0$ , $s_0$ enthalpy and entropy values of dead state reference point respectively | | |

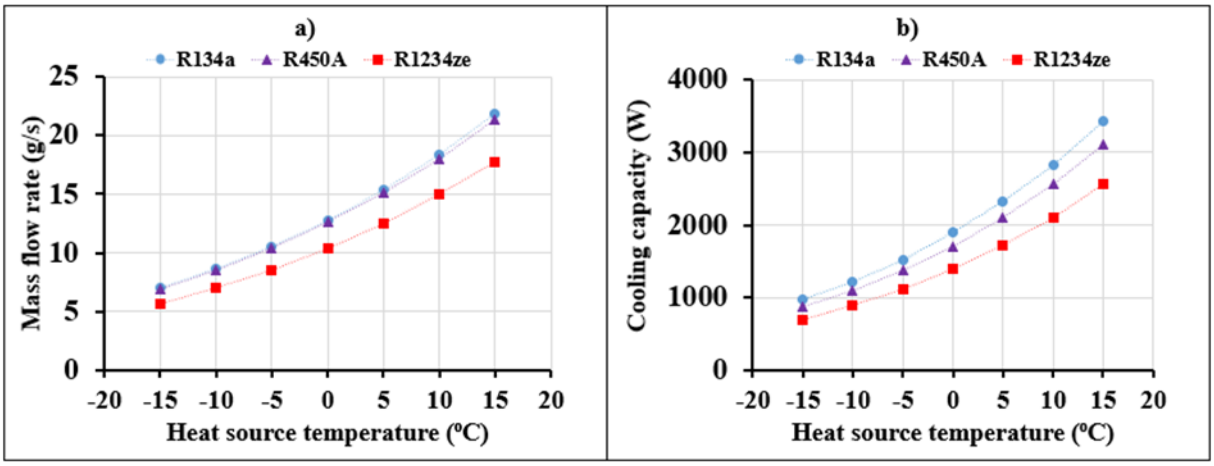


**Fig. 2.** a. Mass flow rate and b. cooling capacity of R134a, R450A and R1234ze

Cooling capacity depends on mass flow rate, cooling effect (Equation 2). The cooling capacity of R134a ranges from 971.87 W to 3422.58 W. R134a has the highest cooling capacity. R450A's cooling capacity ranges from 869.75 W to 3106.45 W. The cooling capacity of R1234ze ranges from 697.37 W to 2563.38 W.

Compressor energy consumption depends on refrigerant's mass flow rate and specific compression work (Equation 3). When using refrigerant R134a, R450A and R1234ze in the cooling system, the change in compressor energy consumption is seen in Figure 3. R134a's compressor energy consumption ranges from 484.43 W to 709.66 W and has the highest compressor energy consumption rate. R450A's compressor energy consumption ranges from 441.24 W to 647.91 W. Compressor energy consumption of R1234ze ranges from 351.70 W to 529.94 W. The refrigerant with the lowest compressor energy consumption is R1234ze.

Discharge temperature is an important parameter in the selection of refrigerant. A high discharge temperature causes the compressor oil to deteriorate and reduces the life of the compressor. Discharge temperatures of refrigerants are given in Figure 3. The discharge temperature of R134a ranges from 74.52 °C to 57.56 °C. The refrigerant with the highest discharge temperature is R134a. The discharge temperature of R450A ranges from 66.80 °C to 53.90 °C. The discharge temperature of R1234ze ranges from 62.62 °C to 51.68 °C. The refrigerant with the lowest discharge temperature is R1234ze. It can be said that using R450A and R1234ze instead of R134a will not pose any problems in terms of discharge temperature.

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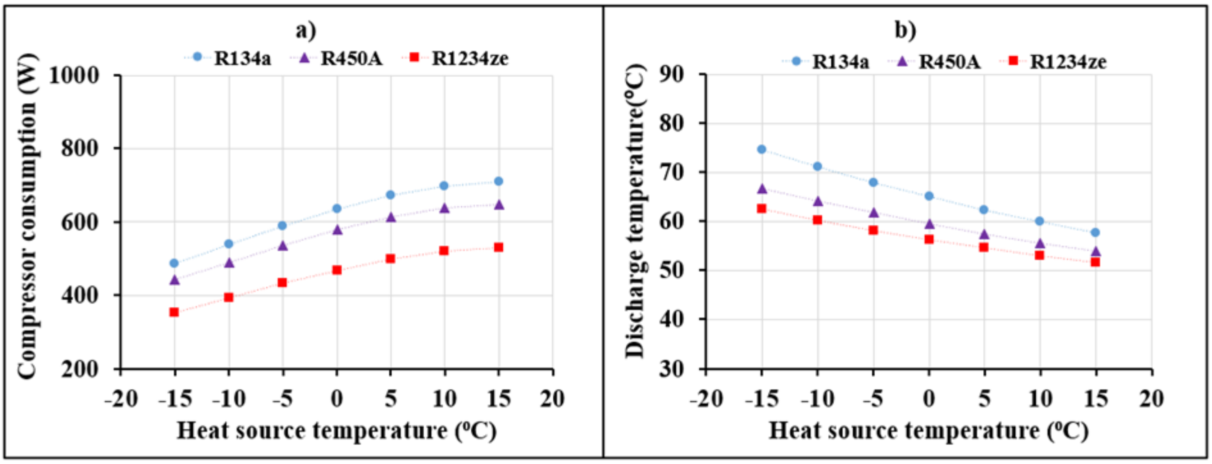


**Fig. 3.** a. Compressor power consumption and b. Discharge temperature for R134a, R450A and R1234ze

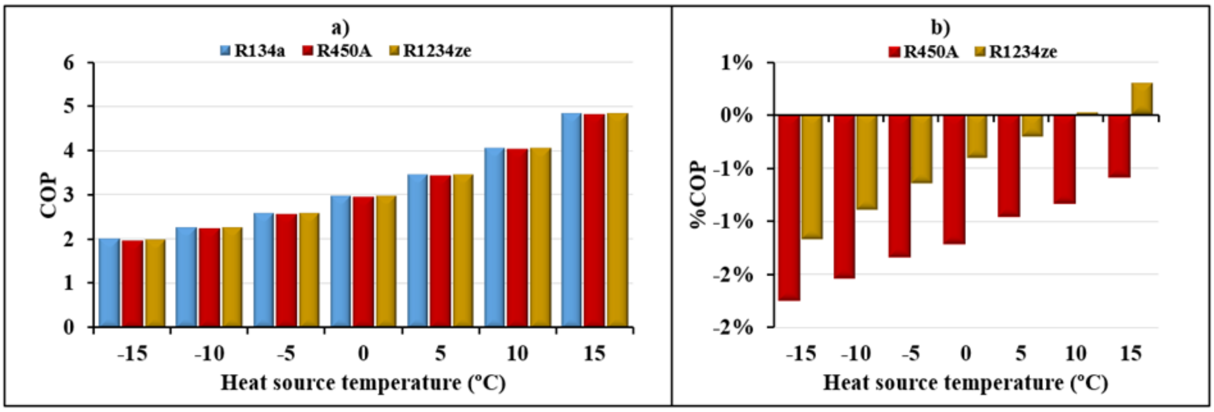


**Figure 4.** a. COP values b. Comparison of COP values with R134a

The COP value of the cooling system depends on the cooling capacity and compressor energy consumption (Equation 5). If R134a, R450A, and R1234ze are used in the system, the change and the percentage changes of R450A and R1234ze compared to R134a are seen in Figure 4. The COP value of R134a ranges from 2.01 to 4.82, while the COP value of R450A ranges from 1.97 to 4.79, and the COP value of R1234ze ranges from 1.98 to 4.84. COP values of R450A and R1234ze are almost similar to R134a.

### 4.2. Exergy analysis results

The total exergy destruction of cooling system and total exergy efficiency are given in Figure 5. Under the given operating conditions, R134a's total exergy destruction rate ranges from 309.82 W to 522.73 w; R450A's ranges from 284.85 W to 478.17 W and R1234ze's ranges from 226.34 W to 389.96 W. The maximum total exergy destruction takes place at R134a, while the lowest is for R1234ze. As the heat source temperature increases, the total exergy destruction rate of the system increases and the total exergy efficiency decreases. It is observed that the total exergy efficiency of refrigerants are close values. As state by the second law of thermodynamics, it was concluded that R450A and R1234ze can be used instead of R134a.

Exergy analysis of all of the cooling system (compressor, condenser, expansion valve and evaporator) was also performed for a detailed analysis. Exergy destruction rates and exergy efficiency of compressor, condenser, expansion valve, evaporator are given in Figure 6, Figure 7, Figure 8 and Figure 9 respectively. In addition, the ratio of exergy destruction of each component of the cooling system for heat source temperature -15 °C and 15 °C to total exergy destruction is presented in Figure 10. It is definite that the most exergy destruction takes place in the compressor. At low heat source temperature, the lowest exergy destruction occurs in the evaporator, while at high heat source temperatures, the minimum exergy destruction occurs in the expansion valve.

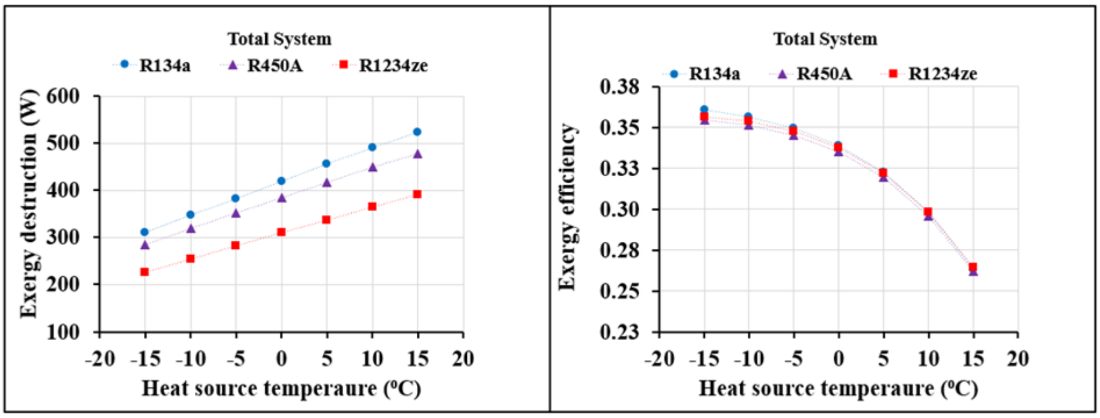


**Fig. 5**. Total exergy destruction rate and total exergy efficiency of cooling system

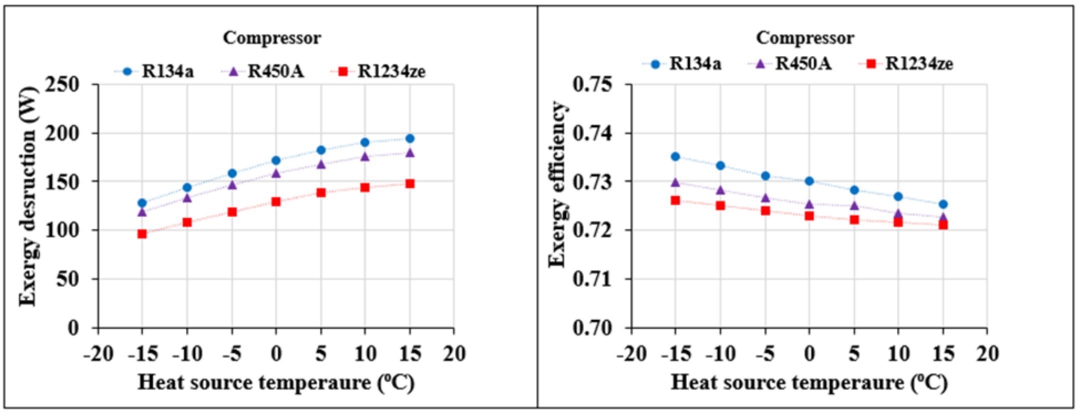


**Fig. 6.** Exergy destruction rate and exergy efficiency of compressor

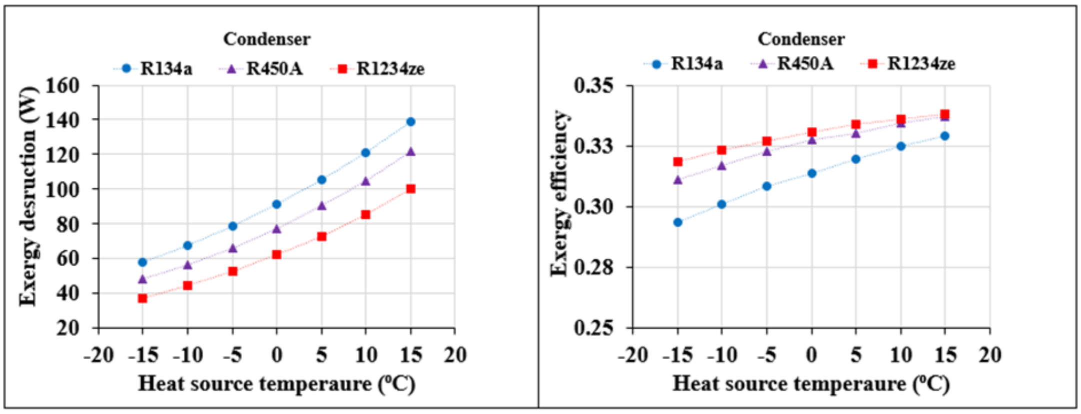


**Fig. 7.** Exergy destruction rate and exergy efficiency of condenser

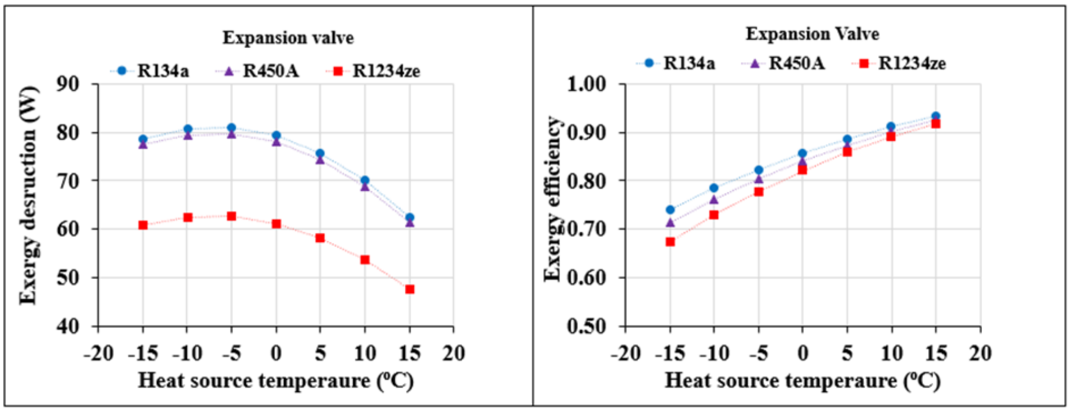


**Fig. 8.** Exergy destruction rate and exergy efficiency of expansion valve

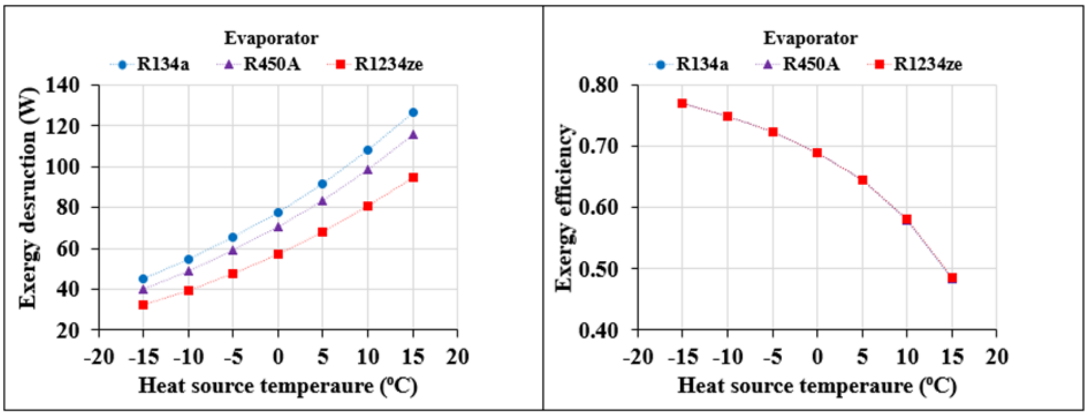


**Fig. 9.** Exergy destruction rate and exergy efficiency of evaporator

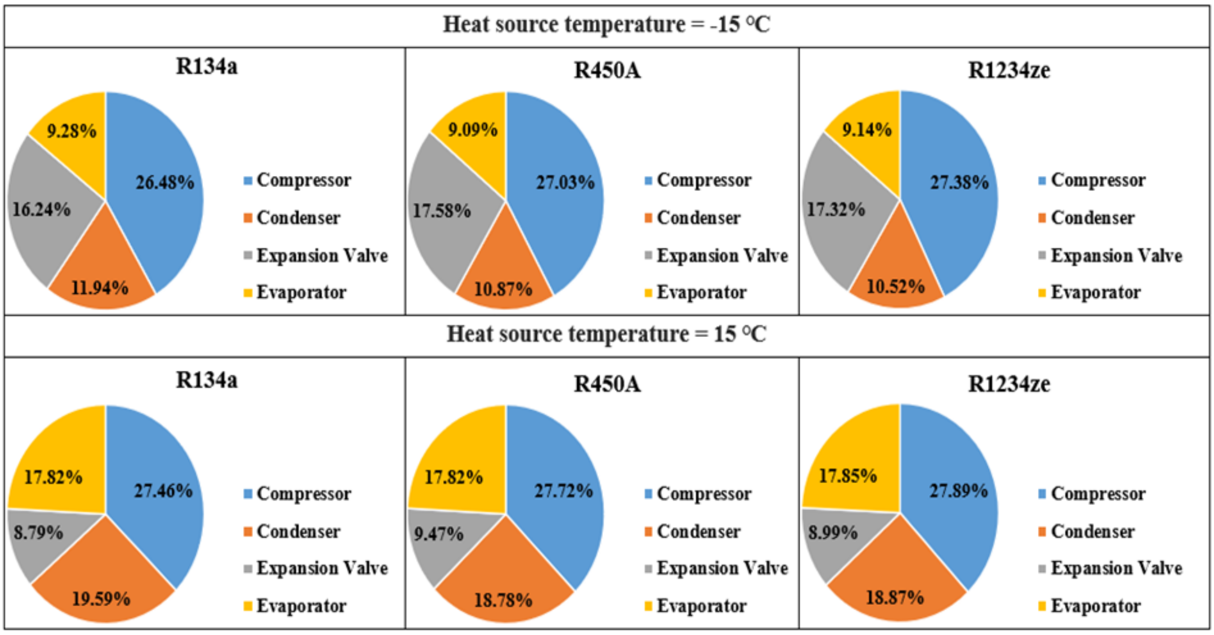


**Fig. 10.** Percentage representation of exergy destruction rate of cooling system components

## 4. Conclusion

In this study, the use of low GWP ratio R450A and R1234ze refrigerants as an alternative to R134a in refrigeration systems was examined. Energy and exergy analysis of the cooling system was performed for R134a, R450A, and R1234ze. The main results from the study are given below:

- The mass flow of refrigerant R134a is higher than R450A and R1234ze. This is because the absorption line density of R134a is higher than R450A and R1234ze.
- The refrigerant with the highest and lowest cooling capacity are R134a and R1234ze.
- R134a is the refrigerant with the highest compressor energy consumption. The refrigerant with the lowest compressor energy consumption is R1234ze.
- The COP value of R134a is slightly higher than R450A and R1234ze.
- The discharge temperature of refrigerant R450A and R1234ze is lower than R134a.
- According to the second law analysis of thermodynamics, it was concluded that R450A and R1234ze can be used instead of R134a.
- For all conditions, the most exergy destruction occurs in the compressor.

As a result, according to first and second law of thermodynamics analysis, it was concluded that R450A and R1234ze, which are low-GWP refrigerants, can be used in cooling systems instead of R134a.

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