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Araştırma Makalesi / Research Article

# Thermodynamic Analysis of Vapor Compression Refrigeration System with Various Refrigerants

Atakan TANTEKİN[1*]

**Abstract**

The study analyzes energy and exergy in the basic vapor compression refrigeration system. The system consists of four parts as expansion valve, condenser, evaporator and compressor. In each component, energy and exergy balance is employed and the effectiveness of the basic vapor compression refrigeration system is presented. In the study, to evaluate the impact of different refrigerants on system effectiveness, four different gases (R134a, R125, R141b, R423a) at constant dead state temperature ($T_0$ = 25 ºC) are analyzed. According to the results, while the COP of R134a is 2.50, the total exergy destruction is 2.31 kW. While the COP of R423a is 0.22, the total exergy destruction is 0.50kW. While the COP of R141b is 0.60, the total exergy destruction is 7.38kW. While the COP of R125 is 0.53, the total exergy destruction is 4.74kW.

**Keywords:** Thermodynamic Analysis, Exergy, Vapor Compression Refrigeration Cycle, Refrigerant.

# Buhar Sıkıştırmalı Soğutma Sisteminin Çeşitli Soğutucularla Termodinamik Analizi

**Öz**

Bu çalışmada, temel buhar sıkıştırmalı soğutma sisteminde enerji ve ekserji analizi yapılmıştır. Sistem, buharlaştırıcı, kompresör, kondenser ve genleşme vanası olmak üzere dört kısımdan oluşmaktadır. Her bir bileşende enerji ve ekserji dengesi kullanılmış ve temel buhar sıkıştırmalı soğutma sisteminin etkinliği ortaya konulmuştur. Çalışmada, farklı soğutucu akışkanların sistem performansına etkisini görmek amacıyla sabit ölü hal sıcaklığında ($T_0$ = 25 ºC) dört farklı gaz (R134a, R125, R141b, R423a) analiz edilmiştir. Sonuçlara göre, R134a'nın COP değeri 2,50 iken toplam ekserji yıkımı 2,31 kW'tır. R423a'nın COP değeri 0,22 iken toplam ekserji yıkımı 0,50 kW'tır. R141b'nin COP değeri 0,60 iken toplam ekserji yıkımı 7,38 kW'tır. R125'in COP değeri 0,53 iken toplam ekserji yıkımı 4,74 kW'tır.

**Anahtar Kelimeler:** Termodinamik Analiz, Ekserji, Buhar Sıkıştırmalı Soğutma Çevrimi, Soğutucu Akışkan.

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## 1. Introduction

One of the topics that are researched and analyzed today is energy. Because energy is an indispensable part of humanity. Energy is very important for people's needs. For example, it has many effects on our nutritional needs, heating and creating a living space. Countries are working to obtain energy resources for their own development and to meet their basic needs. Exergy analysis is performed to make these energy resources more efficient and to increase their usability level. Exergy analysis helps us to see and improve the quality of energy in a system and the level of energy to do work. Today, one of the most important energy sources is fossil fuels. However, the use of fossil fuels causes environmental pollution. With exergy analysis, analyses were made for the potential of energy to do work in the power plant system. Exergy investigation is a convenient method for the analysis and development of thermal systems. It can be employed in a broad variation of systems and helps us find improvements in this system to increase the work potential. The state and size of irreversibility for the whole system are provided by exergy investigation. (Özdil et al., 2018)

Kumar et al. (1989) conducted exergy analyses on a vapor compression refrigeration system utilizing R11 and R12. Exergy and enthalpy charts were provided for both refrigerants to aid the evaluation. By comparing COP and exergetic efficiency of the refrigeration cycle, along with the losses occurring in different components, they aimed to identify a high-performance refrigerant for the system.

Richardson and Butterworth (1995) carried out analyses to evaluate the effectiveness of propane/isobutane mixtures in a vapor compression system. Their findings demonstrated that propane and propane/isobutane mixtures can be utilized in an unmodified R12 system, offering a higher coefficient of performance (COP) compared to R12 under identical operating conditions.

Lee and Su (2002) implemented an investigation on the efficiency of a domestic vapor compression cooling system using isobutane as the refrigerant. The system's COP ranged from 0.8 to 4.5, demonstrating its ability to be compared to a system using R12 refrigerant.

Padilla et al. (2010) investigated for a new refrigerant due to the damage R12 refrigerant caused to the ozone layer. They conducted energy and exergy analyses of twelve refrigerants in a vapor compression refrigeration system. Due to the high ODP of R12 refrigerant and its global warming potential, considering thermodynamic analysis in the vapor compression refrigerant cycle, they concluded that R413a consumes less power in the system and produces less irreversibility, and they preferred this refrigerant.

Ahamed et al. (2011) examined thermodynamic analysis of refrigerants that are less damaging to the ozone layer in the vapor compression refrigeration system. They used R407a, R600a, R410a and R134a refrigerants in the system. They found that the exergy in the system depends on the evaporation temperature, condensation temperature, subcooling and compressor pressure. They found that it also depends on the environmental temperature. Based on the outcomes of the thermodynamic analyses, it was revealed that R134a performed better than other refrigerants.

Baskaran and Koshy (2013) studied COP and exergy losses for R134a, R152a, and RE170 refrigerants in a vapor compression refrigeration cycle. Their results indicated that RE170 outperformed R134a and R152a in both energy and exergy metrics. Additionally, they discovered that at elevated evaporation temperatures, exergy losses across the four components were minimized. The findings also highlighted that RE170 exhibited superior COP and exergetic efficiency compared to the other two refrigerants.

Menlik et al. (2013) performed energy and exergy assessments, along with a performance comparison of R22, R407c and R410a in a vapor compression refrigeration system. Both first and second law analyses were applied to these three refrigerants. The findings revealed that R407c offers a better alternative to R22 compared to R410a, and the condenser was identified as the weakest component of the system.

Chandrasekharan (2014) conducted a comparative investigation to evaluate the influence of refrigerants on the effectiveness of a basic vapor compression refrigeration system, focusing on R12 and R134a. An analytical model using energy and exergy analysis was suggested to examine the impacts of evaporation temperature and subcooling on the COP and exergetic efficiency. In their effort to reduce refrigerator energy consumption, they compared the thermodynamic performance of R134a and R12 refrigerants.

In order to replace R134 with a different refrigerant that has less global warming potential (GWP) and irreversibility, Aized et al. (2022) employed thermodynamic analyses in the vapor compression refrigeration system to determine effectiveness of different refrigerants. They utilized six different refrigerants in the vapor compression refrigerant system to foresee the replacement of R134a refrigerant with refrigerants that have less exergy destruction and less GWP. Various refrigerants were examined in the system: R152a, R600a, R134a, R290, R1234yf and R717. They found that R152 is a liquid with zero ozone depletion potential (ODP) and GWP value of 140, and that it has less exergy destruction and irreversibility. They also experienced that R152a, with its good thermodynamic structure, is easy to use. They stated that R134a is a suitable replacement refrigerant because R152a can be used with a few modifications.

Baghsheikhi and Mohammadi (2023) investigated the performance of an in-row data center cooling system through experimental and analytical methods. A prototype system was placed in a specially designed test room, and its performance was evaluated under varying operating conditions. Thermodynamic and exergy analyses were conducted using a model developed in EES software. The results showed that the system achieved a COP of 3.47 and an exergy efficiency of 19.5%. It was observed that increasing the evaporator temperature improved the COP but reduced exergy efficiency, whereas lowering the condenser temperature enhanced both metrics.

Yılmaz et al. (2024) investigated the energy, exergy, environmental, and enviroeconomic performance of low-temperature vapor compression cascade refrigeration systems using various refrigerants and nanoparticles to enhance efficiency and sustainability. In the study, R290 was utilized in the Low-Temperature Circuit (LTC), while RE170, R1234yf, R600, R600a, and R450A were used in the High-Temperature Circuit (HTC). Nanoparticles such as Al2O3, CNT, CuO, TiO2, ZnO, and SiO2 were incorporated into the refrigerants to assess their impact on system performance. The findings revealed that the R600 nano-refrigerant exhibited the best performance, whereas R1234yf performed the worst. Among the nanoparticles, CuO provided the highest efficiency gains.

The primary objective of this study is to conduct a comprehensive thermodynamic analysis of a vapor compression refrigeration system using different refrigerants. By simultaneously considering energy and exergy assessments under identical operating conditions, the study aims to evaluate the thermodynamic effectiveness of the selected refrigerants. Unlike previous studies that mainly focus on energy analysis, this research provides deeper insights into system irreversibilities and performance potential. Furthermore, it offers a novel evaluation of the relationship between the coefficient of performance and exergy destruction, an aspect that has not been extensively explored in the literature.

## 2. Materials and Methods

The primary aim of the research is to implement an extensive thermodynamic investigation for a vapor compression refrigeration system utilizing four distinct refrigerants. Through energy analysis, the COP of the system was assessed and compared, while the exergy analysis enabled the assessment of exergy destruction across various components. The system comprises four key components as expansion valve, condenser, compressor and evaporator. Within the cycle, the refrigerant is initially compressed to a high pressure in the compressor. It then enters the condenser as superheated vapor, where it releases heat to the surrounding environment. Subsequently, the refrigerant is throttled to a lower pressure via the expansion valve, entering the evaporator in a wet-vapor state. In the evaporator, the refrigerant absorbs heat from the environment, returning to the compressor to repeat the cycle. The configuration of the analyzed system is illustrated in Figure 1, while Table 1 outlines the specific properties of the refrigerants utilized in the analysis. Figure 2 provides a detailed examination of the individual components—evaporator, compressor, expansion valve, and condenser.

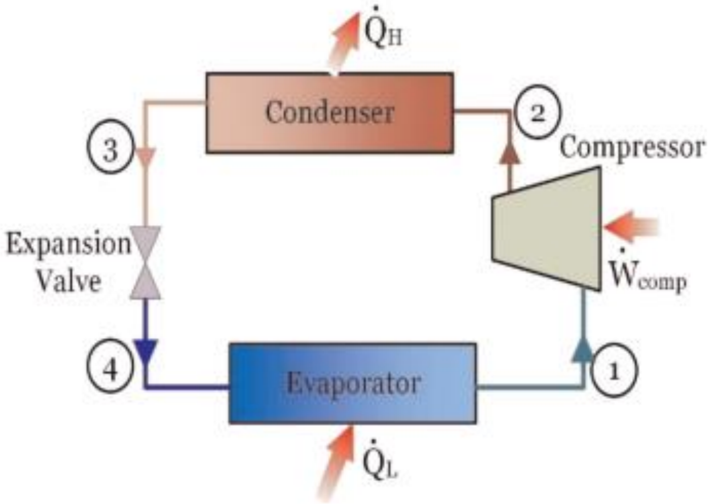


**Figure 1.** Vapor compression refrigeration system. (Seyam, 2019)

**Table 1.** The properties of refrigerants.

| Refrigerant | Molecular Weight (kg/mol) | Normal Boiling Point (°C) | Critical Pressure (kpa) |
|---|---|---|---|
| **R134a** | 102 | -26.09 | 40.59 |
| **R125** | 120 | -48.09 | 36.18 |
| **R141b** | 116.95 | 32.06 | 4212 |
| **R423a** | 126 | -46.12 | 3586 |

The assumptions utilized in the study can be mentioned as;

i. the system is steady state,

ii. the variations in both potential and kinetic energy are ignored,

iii. ideal gas principles are taken into account for fluids.

The first law of thermodynamics expresses that energy cannot be produced or destroyed. In the first law analysis, energy balance and mass equations are used, as seen in Eq. (1) and Eq. (2) (Tantekin and Ozdil, 2017):

Energy input - Energy output = Net Energy ($Q - W = \dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}$) (1)

Mass Input = Mass Output ($\Sigma\dot{m}_{in} = \Sigma\dot{m}_{out}$) (2)

COP is the rate of useful heating or cooling provided for work done. COP can be defined as the ratio of the cooling capacity of the evaporator to the input power of the compressor. COP is shown as in Eq. (3):

$$COP = Q_e / W = (h_1 - h_4) / (h_2 - h_1) \quad (3)$$

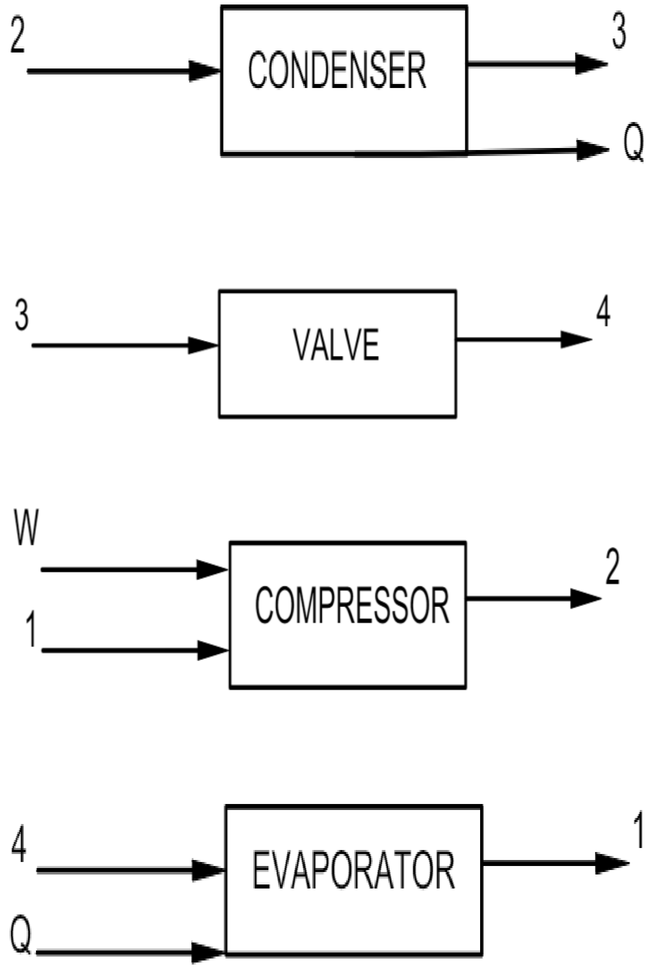


**Figure 2.** Schematic diagram of the components of the vapor compression refrigerant system.

The energy balance equation for the evaporator, which is the component of the system, can be found using Eq. (4):

$$Q_e + \dot{m}_4 h_4 = \dot{m}_1 h_1 \quad (4)$$

The energy balance equation for the compressor, which is the component of the system, can be found using Eq. (5):

$$\dot{m}_1 h_1 + W = \dot{m}_2 h_2 \quad (5)$$

The energy balance equation for the condenser, which is the component of the system, can be found using Eq. (6):

$$\dot{m}_2 h_2 + Q_c = \dot{m}_3 h_3 \quad (6)$$

The energy balance equation for the valve, which is the component of the system, can be found using Eq. (7):

$$\dot{m}_3 h_3 = \dot{m}_4 h_4 \quad (7)$$

Exergy indicates the forward operation of the system. Exergy destruction refers to the performance and efficiency of the system.

Exergy balance equations can be expressed as Eq. (8):

Exergy input - Exergy output - Exergy consumed reversibility - Exergy destruction = Net exergy (8)

The general exergy formula is shown in Eq. (9):

$$ex = (h - h_0) - T_0(s - s_0) \quad (9)$$

The Exergy Balance equation for the evaporator, which is the component of the system, can be calculated from Eq. (10):

$$\dot{m}_4 ex_4 + Q_e(1 - T_o/T_e) = \dot{m} ex_1 + Ex_d \quad (10)$$

The Exergy Balance equation for the compressor, which is the component of the system, can be calculated from Eq. (11):

$$W + \dot{m}_1 ex_1 = \dot{m}_2 ex_2 + Ex_d \quad (11)$$

The Exergy Balance equation for the condenser, which is the component of the system, can be calculated from Eq. (12):

$$\dot{m}_1 ex_2 = \dot{m} ex_3 + Ex_d + Q_c(1\text{-}T_o/T_e) \quad (12)$$

The Exergy Balance equation for the valve, which is the component of the system, can be calculated from Eq. (13):

$$\dot{m}_3 ex_3 = \dot{m}_4 ex_4 + Ex_d \quad (13)$$

## 3. Findings and Discussion

In the paper, first and second law analyses were performed using different refrigerants in the basic vapor compression system. Then, COP and exergy destruction values were compared between refrigerants. COP, exergy rates and exergy destructions of the system in different refrigerants are given in Tables 2 - 10. First, COP values were calculated to observe the first law performance. When comparing the results, according to Table 2, the COP value of the system using R134a refrigerant is 2.50, while the COP value of the system using R423 refrigerant is 0.22. The COP value of the system using R134a refrigerant is higher than the system using R423a refrigerant. According to Table 2, the COP value of the system using R141b refrigerant is 0.60. The COP value of the system using R125 refrigerant is 0.53. Then, second law analysis was performed and comparisons were made. According to Table 4 and Table 8, the exergy destruction value of the system using R134a refrigerant is 2.31 kW. The exergy destruction value of the system using R423a refrigerant is 9.22 kW. According to Table 6 and Table 10, the exergy destruction value of the system using R141b refrigerant is 7.38kW. The exergy destruction value of the system using R125 refrigerant is 4.74kW. The refrigerant with the least exergy destruction is R134a.

**Table 2.** COP values of the system for various refrigerants.

| Refrigerants | COP |
|---|---|
| R134a | 2.50 |
| R423a | 0.22 |
| R141b | 0.60 |
| R125 | 0.53 |

**Table 3.** Exergy ratio values for R134a in dead-state conditions.

| State | Refrigerant Type | Mass flow rate (kg/s) | Temperature (K) | Pressure (kPa) | Enthalpy (kJ/kg) | Entropy (kJ/kgK) | Ex (kW) |
|---|---|---|---|---|---|---|---|
| **0** | R134a | - | 298.15 | 101.32 | 276.4 | 1.10 | - |
| **1** | R134a | 0.07 | 253 | 120 | 238.8 | 0.95 | 0.49 |
| **2** | R134a | 0.07 | 333 | 800 | 296.8 | 1.01 | 3.38 |
| **3** | R134a | 0.07 | 303 | 800 | 93.58 | 0.34 | 2.99 |
| **4** | R134a | 0.07 | 250.68 | 120 | 22.3 | 0.09 | 2.40 |

**Table 4.** Exergy destruction of components in the system for R134a.

| Components | $Ex_d$ (kW) |
|---|---|
| Evaporator | 0.05 |
| Compressor | 1.16 |
| Condenser | 0.50 |
| Valve | 0.60 |
| Total | 2.31 |

**Table 5.** Exergy ratio values for R141b in dead-state conditions.

| State | Refrigerant Type | Mass flow rate (kg/s) | Temperature (K) | Pressure (kPa) | Enthalpy (kJ/kg) | Entropy (kJ/kgK) | Ex (kW) |
|---|---|---|---|---|---|---|---|
| **0** | R141b | - | 298.15 | 101.32 | 67.35 | 0.2535 | - |
| **1** | R141b | 0.07 | 253 | 120 | 19.41 | 0.08 | 3.40 |
| **2** | R141b | 0.07 | 333 | 800 | 110 | 0.38 | 3.33 |
| **3** | R141b | 0.07 | 303 | 800 | 73.85 | 0.27 | 3.17 |
| **4** | R141b | 0.07 | 250.68 | 120 | 16.96 | 0.069 | 3.13 |

**Table 6.** Exergy destruction of components in the system for R141b.

| Components | $Ex_d$ (kW) |
|---|---|
| Evaporator | 0.42 |
| Compressor | 6.41 |
| Condenser | 0.50 |
| Valve | 0.04 |
| Total | 7.38 |

**Table 7.** Exergy ratio values for R423a in dead-state conditions.

| State | Refrigerant Type | Mass flow rate (kg/s) | Temperature (K) | Pressure (kPa) | Enthalpy (kJ/kg) | Entropy (kJ/kg-K) | Ex (kW) |
|---|---|---|---|---|---|---|---|
| **0** | R423a | - | 298.15 | 101.32 | 233.3 | 0.9235 | - |
| **1** | R423a | 0.07 | 253 | 120 | 119 | 0.47 | 2.12 |
| **2** | R423a | 0.07 | 333 | 800 | 255.2 | 0.86 | 3.53 |
| **3** | R423a | 0.07 | 303 | 800 | 88.53 | 0.325 | 3.09 |
| **4** | R423a | 0.07 | 252.88 | 120 | 48.57 | 0.193 | 2.58 |

**Table 8.** Exergy destruction of components in the system for R423a.

| Components | $Ex_d$ (kW) |
|---|---|
| Evaporator | 0.06 |
| Compressor | 8.14 |
| Condenser | 0.50 |
| Valve | 0.52 |
| Total | 9.23 |

**Table 9.** Exergy ratio values for R125 in dead-state conditions.

| State | Refrigerant Type | Mass flow rate (kg/s) | Temperature (K) | Pressure (kPa) | Enthalpy (kJ/kg) | Entropy (kJ/kg-K) | Ex (kW) |
|---|---|---|---|---|---|---|---|
| **0** | R125 | - | 298.15 | 101.32 | 361.6 | 1.711 | - |
| **1** | R125 | 0.07 | 253 | 120 | 327.21 | 1.57 | -6.23 |
| **2** | R125 | 0.07 | 333 | 800 | 384.22 | 1.64 | -3.72 |
| **3** | R125 | 0.07 | 303 | 800 | 357.53 | 1.56 | -3.86 |
| **4** | R125 | 0.07 | 250.68 | 120 | 325.4 | 1.56 | -6.42 |

**Table 10.** Exergy destruction of components in the system for R125.

| Components | $Ex_d$ (kW) |
|---|---|
| Evaporator | 0.19 |
| Compressor | 1.48 |
| Condenser | 0.50 |
| Valve | 2.56 |
| Total | 4.74 |

According to Figure 3, the COP value of the system using R134a refrigerant is higher. The cooling performance of the system using R134a refrigerant is better than systems using other refrigerants. According to Figure 4, the exergy destruction values of 4 different refrigerants are given as percentages. The refrigerant that causes the lowest exergy destruction in the system is R134a.

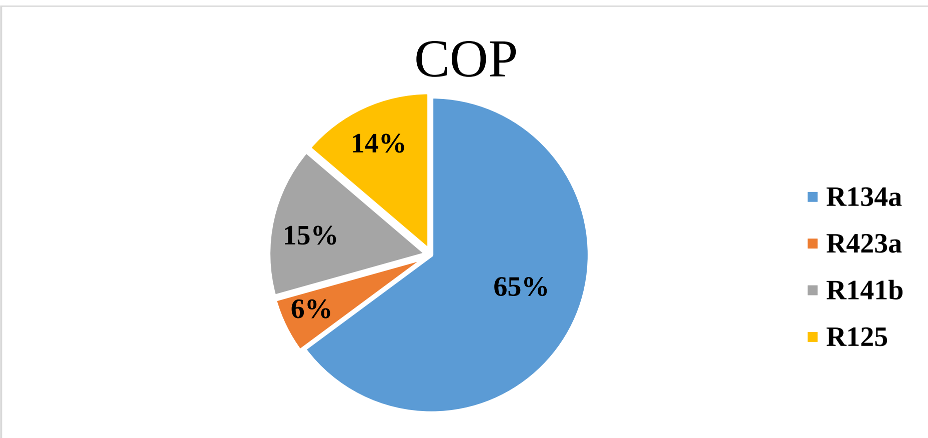


**Figure 3.** Distribution of COP rates of the refrigerants used in the system.

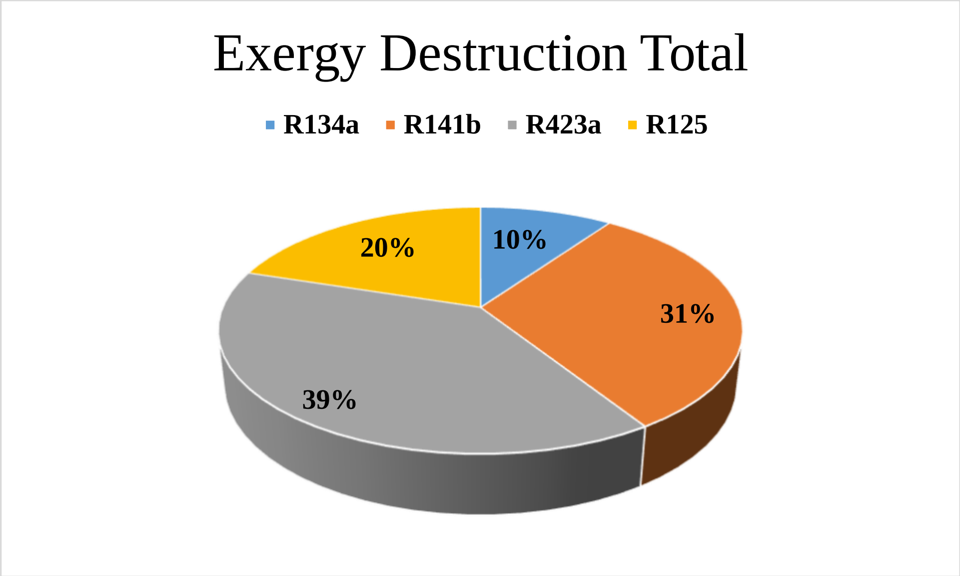


**Figure 4.** Distribution of exergy destruction rates of the refrigerants used in the system.

## 4. Conclusions and Recommendations

In this analysis, investigations were made based on the first and second laws of thermodynamics for the vapor compression refrigeration cycle. According to the results of the first law analysis, the COP value of R134a is calculated as 2.50. The COP value of R125 is calculated as 0.53. The COP value of R141b is found to be 0.60. The COP value of R423a is found to be 0.22. According to the outcomes of the second law of analysis, the exergy destruction of the system using R134a refrigerant is found to be 2.31 kW. The exergy destruction of R125 refrigerant is found to be 4.74. The exergy destruction of R141b refrigerant is calculated as 7.38. The exergy destruction of R423a refrigerant is calculated as 9.23. As a result of these analyses, the cooling performance of R134a was found to be better compared to other refrigerants. As a future study, the effect of using different fluids in more complex systems on system energy and exergy efficiency can be investigated.

## Nomenclature

COP Coefficient of Performance (–)

Ex Exergy (kJ)

$Ex_d$ Exergy destruction (kW)

h Specific enthalpy (kJ/kg)

$\dot{m}$ Mass flow rate (kg/s)

Q Heat transfer rate (kW)

s Specific entropy (kJ/kg·K)

T Temperature (°C)

W Work done (kW)

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## Statement of Conflicts of Interest

There is no conflict of interest.

## Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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