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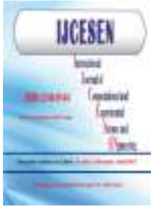

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Research Article

Exergy Analyses of Vehicles Air Conditioning Systems for Different Refrigerants

Arzu KEVEN*

Golcuk Vocational School, Kocaeli University, Kocaeli, Turkey
* **Corresponding Author** : **Email:** arzu.keven@kocaeli.edu.tr - **ORCID:** 0000-0003-0040-9167

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Abstract:

There are a limited number of studies in the literature that include detailed exergy analysis of vehicle air conditioning systems. In this study, in order to increase the performance of the air conditioning system in vehicles, a detailed exergy analysis has been made with the assumption that different refrigerants are used. R-134A, R-E245cb2, R-404A, R-1234ze(Z), R-161, R-1234zd(E), R-513A, R-1234ze(E) and R-1234yf has been chosen as the refrigerant. In the analysis, a comparison has been made by considering the environment, performance and safety values. While the COP values of the cycles increase with increasing evaporator temperatures, the COP values decrease at increasing condenser temperatures. On the other hand, exergy efficiency decreases with increasing evaporator and condenser temperatures. Also, it is aimed to evaluate all the elements of a vehicle air conditioning system with exergy analysis..

1. Introduction

Air conditioning and refrigeration is getting more important in our daily life and industry. In our daily life air conditioning and refrigeration are used in home, vehicles and other cooling demands. In industry, cooling, refrigeration and cryogenic applications are used widely. Many studies are carried out about the performance and exergy analyses of these applications [1, 2, 3]. There is an air conditioning system operating according to the vapor compression refrigeration cycle in the vehicles. and the compressor is powered directly from the internal combustion engine. Many studies are carried out to reduce losses and emissions in vehicle air conditioning systems. In the literature, studies on vehicle air conditioning have generally focused on improving driver comfort conditions, using different refrigerants, optimizing air conditioning elements and working conditions [4]. In addition to these studies, there are studies on refrigerants such as R-152a, R-430a, R-290, which can be an alternative to R-13a refrigerant in vehicle air conditioning systems [5-11]. Many studies have been conducted to determine the appropriate design of a bus air conditioner [12-14]. From the experimental studies, it has been obtained that the R-513A and 410-a refrigerant has higher performance than R-134a the refrigerants [15,16]. Also, Unal [17] is studied on the thermodynamic analysis of the vapor-compression refrigeration system with a two-phase ejector. The air conditioning system used in vehicles needs energy to operate. The energy source used in vehicles is fuel. Chemical energy is converted into mechanical work by burning fuel in the vehicle engine. Again, the alternator in the vehicle generates electrical energy with the mechanical drive it receives from the engine. All systems and elements in the vehicle consume mechanical or electrical energy during their operation. The place with the highest energy consumption in the air conditioning system is the compressors. Power consumption values must be determined in order to determine the net effect of the compressor in the air conditioning system on the engine. The refrigerants used in the air conditioning system also have a decisive effect on the efficient and effective operation of the air conditioning system. In this study, in order to increase the performance of bus air conditioners, detailed thermodynamic calculations of the cycles were done by using R-134A, R-E245cb2, R-404A, R-1234ze(Z), R-161, R-1234zd(E), R-513A, R-1234ze(E) and R-1234yf as the refrigerants. In the analyses, also a comparison has been studied by taking into account the safety values, environment and performance. The environmental friendliness of the analyzed refrigerants is also important. Thus, in this study, it is aimed to recommend energy saving and environmentally friendly refrigerants in air conditioning systems. The results have been given in tables and graphs.

2. Material and Methods

2.1. Description of the vapor-compression refrigeration system (VCRS)

In the vapor compression mechanical cooling system, the refrigerant compressed in the compressor enters the condenser as vapor, as can be seen in Figure 1. In the condenser, the refrigerant condenses by giving off heat to the environment. Then, the refrigerant as a liquid enters in the throttling valve, and in the evaporator absorbs the heat of the cooling medium and cools the medium. The cycle repeats as the refrigerant in saturated vapor state from the evaporator, and goes to the compressor.

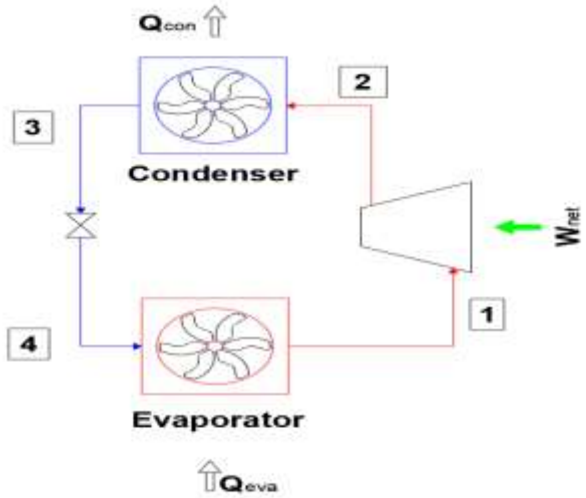

Figure 1. *The vapor-compression refrigeration system (VCRS)*

The main purposes of the use of vehicle air conditioning systems can be listed as heating, cooling and dehumidification processes. Vehicle air conditioning systems basically operate on a vapor compression refrigeration cycle [18]. An ideal vehicle air conditioning (AAC) system provides the appropriate temperature and humidity for human comfort [19].

2.2. Thermodynamic modelling

The equations, used in system analysis are given below.

The mass balances:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

The energy balance:

$$\sum \dot{Q} - \sum \dot{W} = \sum H_{out} - \sum H_{in} \quad (2)$$

The performance coefficients of the analyzed cycles are calculated as follows:

$$COP_{vapour-comp} = Q_{eva}/W_{comp} \quad (3)$$

The exergy balance for the analyzed cycles is as follows [20].

$$\sum m_{in}\, e_{in} - \sum m_{out}\, e_{out} + \sum Q(1 - T/T_0 - \sum W - E_D = 0 \quad (4)$$

Specific exergy is;

$$e = (h - h_0) - T_0(s - s_0) \quad (5)$$

The exergy efficiency of the CRS

$$\eta_{ex} = \text{Exergy in product}/\text{Exergy of fuel} \quad (6)$$

3. Results and Discussions

3.1. Safety characteristics

The world is currently dealing with pollution and climate change. Also, there are a real need for a solution of a sustainable developments in industrial sectors. Pollution levels are skyrocketing as the automobile industry expands daily [14]. In this context, fluids that may be suitable for vehicle air conditioners have been examined in this study. The refrigerants physical, safety and environmental data analyzed in our study are given in Table 1 [21]. It has been seen in this study that R-1233ze(Z) refrigerant is the best refrigerant compared to other refrigerants according to the performance data of these refrigerants. In addition, environmental and safety data values are also good compared to other refrigerants, but due to the flammability of this refrigerant, necessary safety measures are needed. The same is true for R-1234ze(E) and R-1234yf refrigerant. Although the ODP value of the R-E245cb2 refrigerant is zero, its GWP value is high. Although the ODP values of R-404A, R-134A and R-513A refrigerants are 0, they have high GWP values, which is the biggest disadvantage of these refrigerants.

3.2. Effect of evaporator temperature on performance parameters

For refrigerants selected as R-134A, R-E245cb2, R-404A, R-1234ze(Z), R-161, R-1234zd(E), R-513A, R-1234ze(E) and R-1234yf, detailed analyses have been made according to the first and second laws of thermodynamics for different evaporator and condenser temperatures. Analyses results according to different evaporator temperatures are given in Figure 2-11. The operating conditions accepted for the analyses are T_{con}= 313 K, and the refrigeration capacity is 26 kW. Figure 2 shows that the COP values increase as the evaporator temperatures increase. Among the analyzed refrigerants, the highest COP value belongs to R-1234ze(Z) refrigerant, followed by R-1234zd(E) and R-161 refrigerants, respectively. It has been observed that the lowest COP value belonged to the R-404A refrigerant.

Table 1. *Physical, environmental and safety data of analyzed refrigerants.*

Refrig.	Mol. weight (g/mol)	Critical Temp. (ºC)	ASHRAE 34 Safety	ODP	GWP
R-134A	102.03	101.10	A1	0	1430
R-161	48.06	102.2	A1	0	12
R-404A	97.60	72	A1	0	3900
R-513A	108.40	96.50	A1	0	573
R-1234ze(E)	114.04	-19.12	A2	0	4
R-1234yf	114	94.70	A2	0	4
R-1233zd(E)	130.50	154	A1	0	7
R-1234ze(Z)	114.04	150.1	A2	0	1
R-E245cb2	150.04	133.663	-	0	680

In addition, R-1234ze(Z) is classified as A2, which has some flammability while the component R-1234zd(E) and R-161 have a flame-retardant effect. Thus, R-1234zd(E) and R-1234ze(Z) refrigerants can be recommended as an alternative to R134a in vehicles.

As the evaporator temperatures increase, the compressor work required for the cooling system decreases (Figure 3). In Figure 3, it is also seen that the highest compressor work belongs to the R-404A refrigerant, and the lowest compressor work belongs to the R-1234ze(Z) refrigerant at increasing evaporator temperatures. Figure 4 shows the variation of the mass flow rate ratio with increasing evaporator temperature. In all refrigerants, the mass flow rate decreases with increasing evaporator temperatures. The highest and lowest mass flow rate ratios consist at R-404A and R-161 refrigerants. In addition, Figure 5 shows the heat values released from the condenser decreases with increasing evaporator temperatures. While the highest heat values thrown from the condenser belong to the R404A and R-1234yf refrigerant, it is seen that the lowest value belongs to the R-1234ze(Z) refrigerant (Figure 5). In Figure 6, the second law efficiency values of the analyzed refrigerants are given for different evaporator temperatures. The exergy efficiency decreases with increasing evaporator temperatures. It has been observed that the highest second law efficiency value belonged to the R-1234ze(Z) refrigerant, while the lowest efficiency value obtained at the R-404A refrigerant. It is also seen from the figure that the second law efficiency of the R-1234zd(E) refrigerant is 4.68% lower than

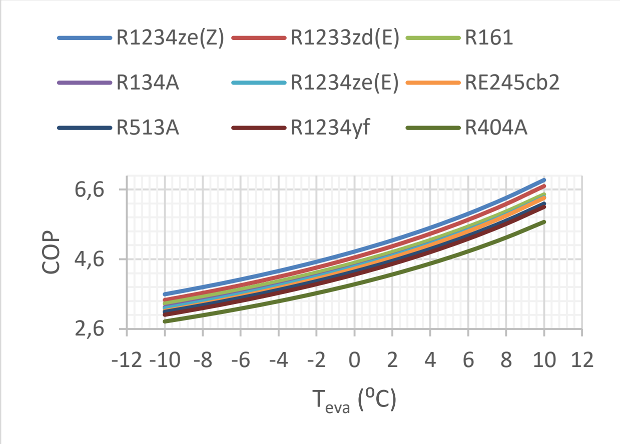

Figure 2. *Variation of the COP with evaporator temperatures of the refrigerants.*

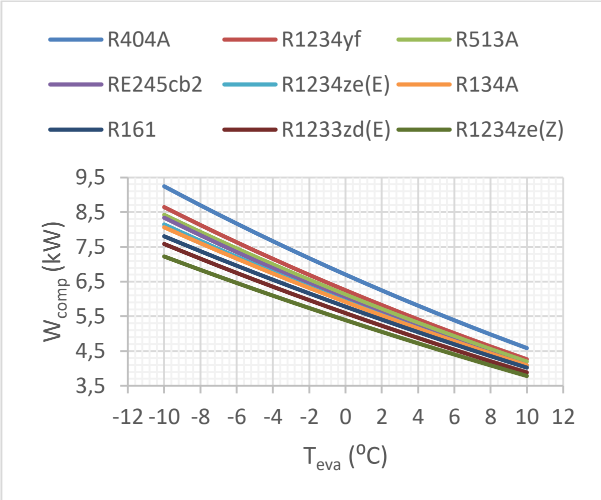

Figure 3. *Variation of the W_{comp} with the evaporator temperatures of the refrigerants*

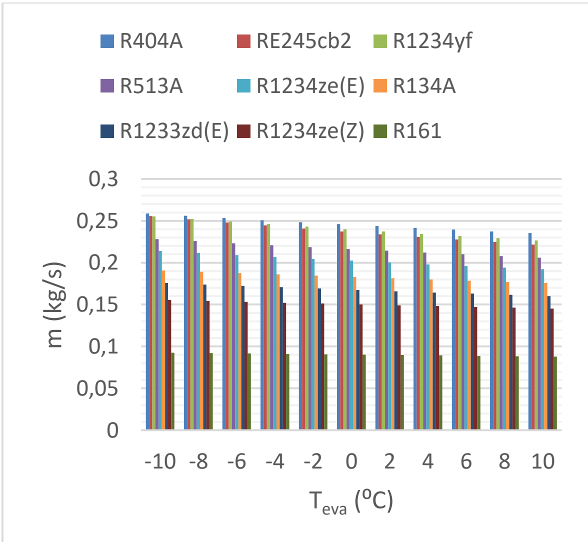

Figure 4. *Variation of the mass flow rate ratio with the evaporator temperatures of the refrigerants.*

the R-1234ze(Z) refrigerant. The total exergy destruction value of the system in the analysis performed at different evaporator temperatures is given in Figure 7. The highest exergy destruction

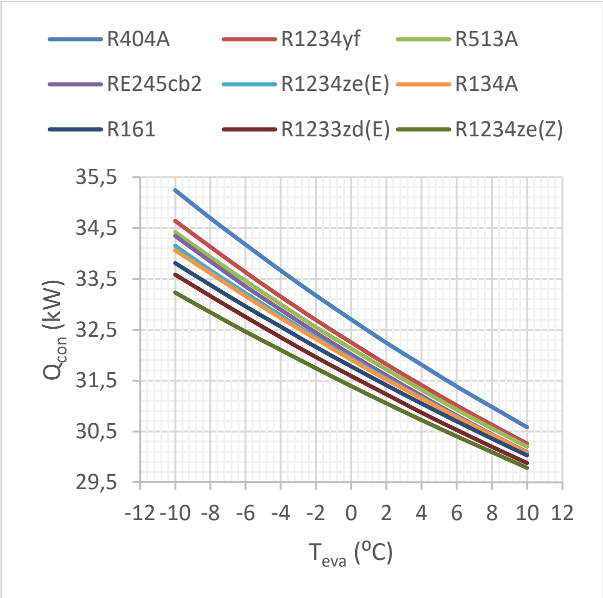

Figure 5. *Variation of the* Q_{con} *with the evaporator temperatures of* the *refrigerants.*

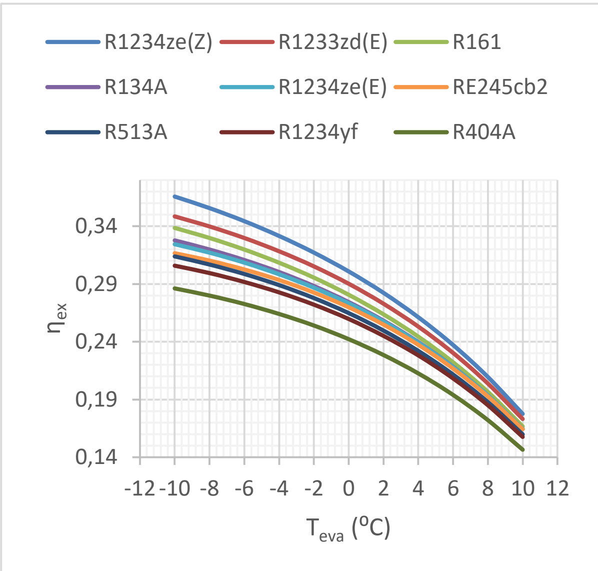

Figure 6. *Variation of the* η_{ex} *with the evaporator temperatures of the refrigerants.*

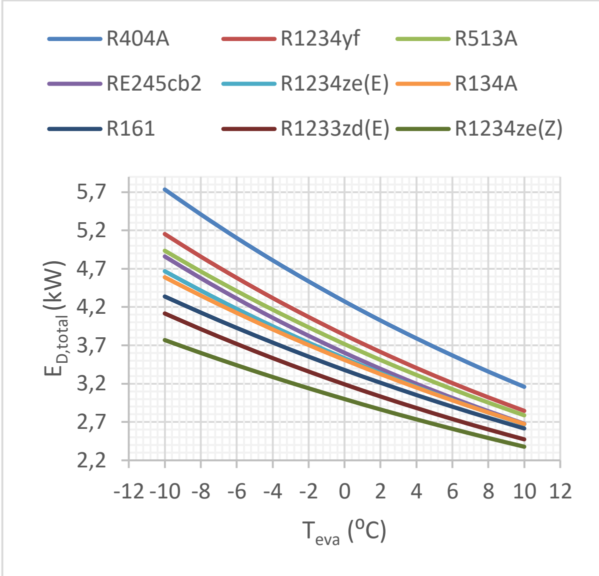

Figure 7. *Variation of the* $E_{D,total}$ *with the evaporator temperatures of the refrigerants.*

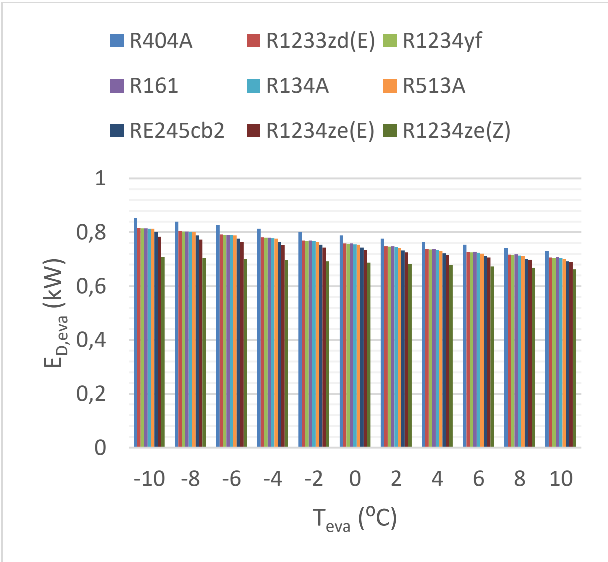

Figure 8. *Variation of the* $E_{D,eva}$ *with the evaporator temperatures of the refrigerants.*

values obtained from R-404A, the lowest values were obtained for R-1234ze(Z). In the analysis, the total exergy destruction value of each system element performed at different evaporator temperatures is shown in from Figure 8 to Figure 11. In all refrigerants, exergy destruction decreases with increasing evaporator temperatures (Figure 8). The highest exergy destruction values belong to R-404A, followed by R-1234zd(E), R-1234yf and R-161 in the evaporator. The lowest values have been obtained for R-1234ze(Z) (Figure 8). In Figure 9, similarly, the exergy destruction decreases with increasing evaporator temperatures for all the refrigerants in the condenser.

Figure 9 illustrates that the highest exergy and the lowest destruction values in the condenser belong to R-161 and R-1234zd(E), respectively. In addition, it is seen from the Figure 9 that the highest exergy destruction values belong to the refrigerant R-404A, 1234ze(Z) and R-134A. In Figure 10, it is seen that the highest exergy destruction values in the compressor belong to the R-404A refrigerant. On the other hand, the lowest exergy destruction values were obtained for R-1233ze(Z). It shows that the highest and the lowest exergy destruction values in the throttling valve have been obtained in R-404A and R-1233ze(Z), respectively (Figure 11). In all the refrigerants, the exergy destruction decreases with the increasing evaporator temperatures.

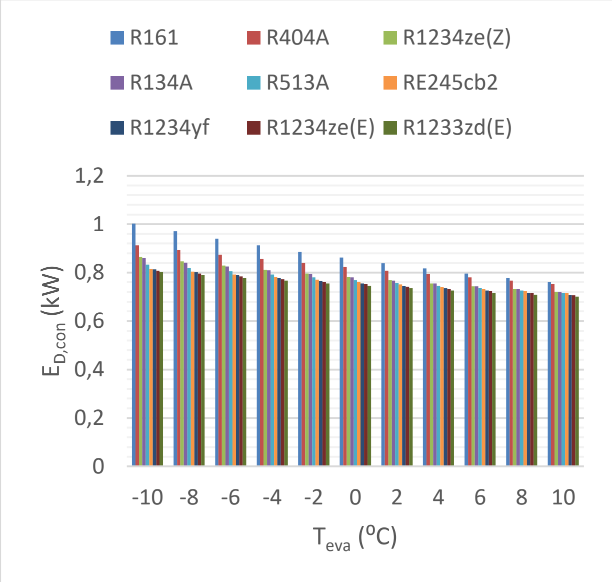

Figure 9. *Variation of the $E_{D,con}$ with the evaporator temperatures of the refrigerants.*

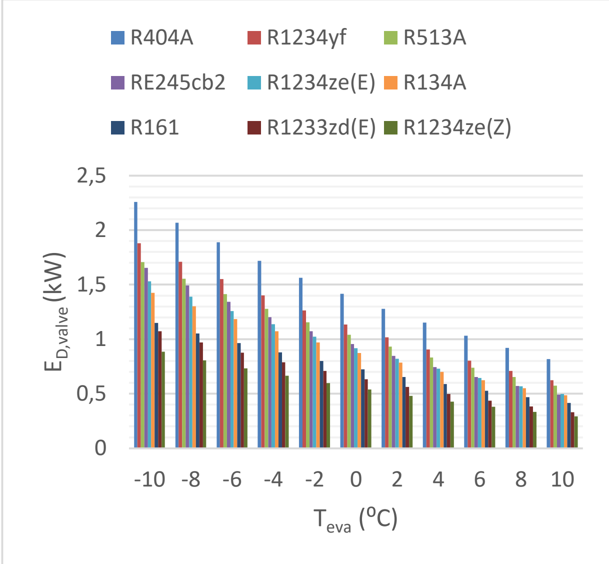

Figure 11. *Variation of the $E_{D,valve}$ with the evaporator temperatures of the refrigerants.*

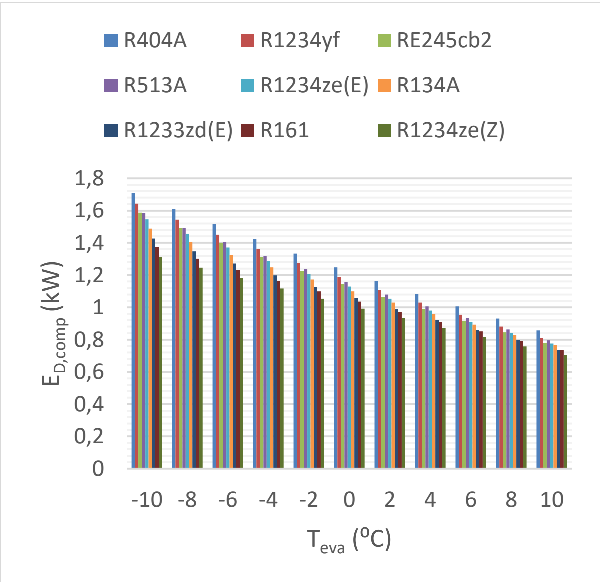

Figure 10. *Variation of the $E_{D,comp}$ with the evaporator temperatures of the refrigerants.*

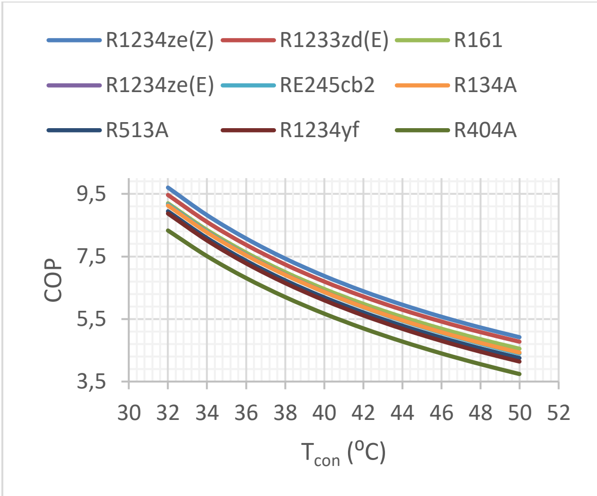

Figure 12. *Variation of the COP with the condenser temperatures of the refrigerants.*

3.3. Effect of condenser temperature on performance parameters

Analysis results according to different evaporator temperatures are given from Figure 12 to Figure 21. The operating conditions accepted for the analysis were T_{eva}= 283 K, and the refrigeration capacity was 26 kW. It is seen this the COP values decrease as the condenser temperatures increase (Figure 13). While the maximum COP value was obtained from the R-1234ze(Z) refrigerant among the analyzed refrigerants, it has seen that the lowest COP value was obtained from R-404A refrigerant. In Figure 13, the highest compressor work at increasing the condenser temperatures belongs to R-404A refrigerant, followed by R-1234yf and R-513A refrigerants, respectively. It is seen that the lowest compressor work belongs to the R-1234ze(Z) refrigerant under the same operating conditions. Figure 14 shows the variation of the mass flow rate ratio with increasing condenser temperature. The highest and lowest mass flow rates occur when using R-404A and R-161. As the condenser temperature increases, the mass flow rates of the refrigerants also increase. In Figure 15, it is seen that the heat values released from the condenser increase according to the increasing condenser temperatures for all the refrigerants. It is seen that the highest heat values from the condenser belong to the R-404A, R-1234yf and R-513A refrigerants, respectively. The exergy efficiency of the refrigerants examined in the analysis decreases with increasing the condenser temperature.

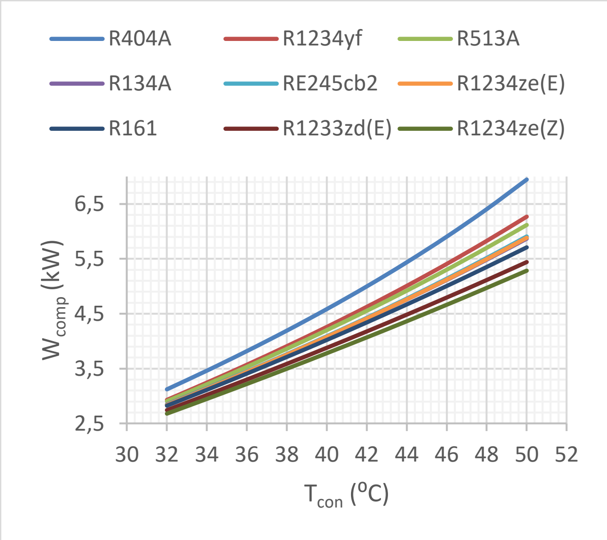

Figure 13. *Variation of the W_{comp} with the evaporator temperatures of the refrigerants.*

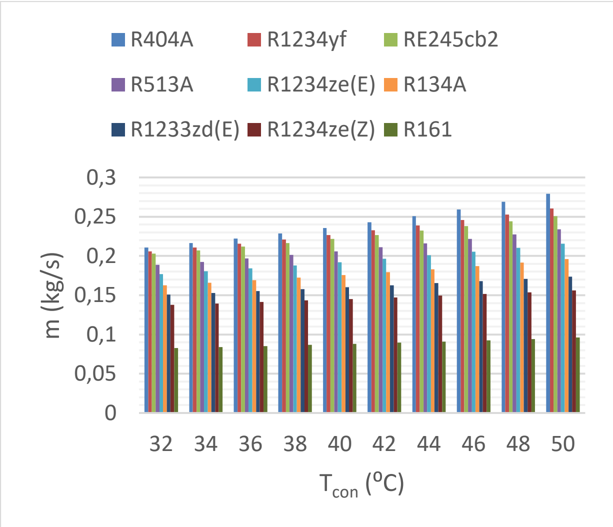

Figure 14. *Variation of the mass flow rate ratio with the condenser temperatures of the refrigerants.*

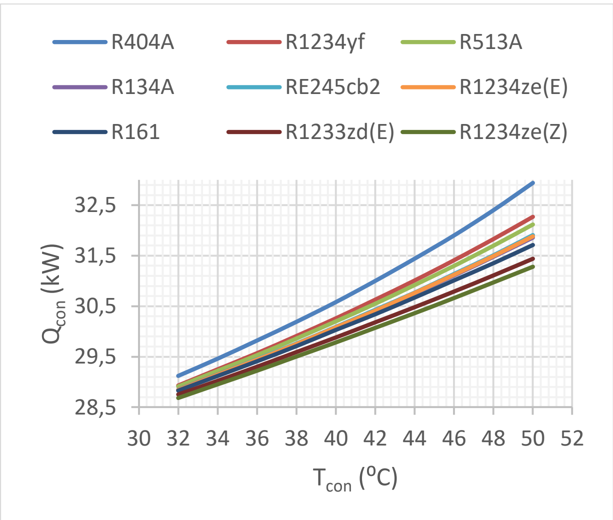

Figure 15. *Variation of the Q_{con} with the condenser temperatures of the refrigerants.*

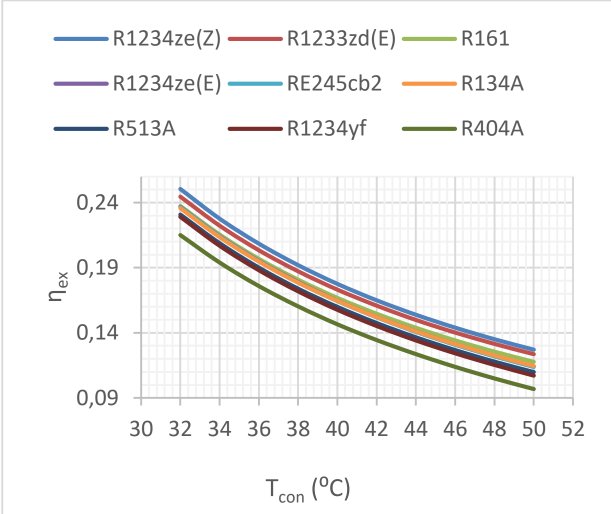

Figure 16. *Variation of the η_{ex} with the condenser temperatures of the refrigerants.*

In Figure 16, it is seen that the highest second law efficiency value belongs to R-1234ze(Z) refrigerant, while the lowest efficiency value belongs to R-404A refrigerant at increasing the condenser temperatures. Total exergy destruction is very important in exergy analysis as it provides information about the energy quality degradation. The total exergy destruction value of the system in the analysis performed at different condenser temperatures is shown in Figure 17. As the condenser temperature increases, the total exergy destruction also increases. In Figure 17, the highest exergy destruction values at increasing condenser temperatures belong to R-404A, R-1234yf and R-513A refrigerants, respectively. It is seen that the lowest exergy destruction belongs to the R-1234ze(Z) refrigerant. The total exergy destruction value of each components performed at different condenser

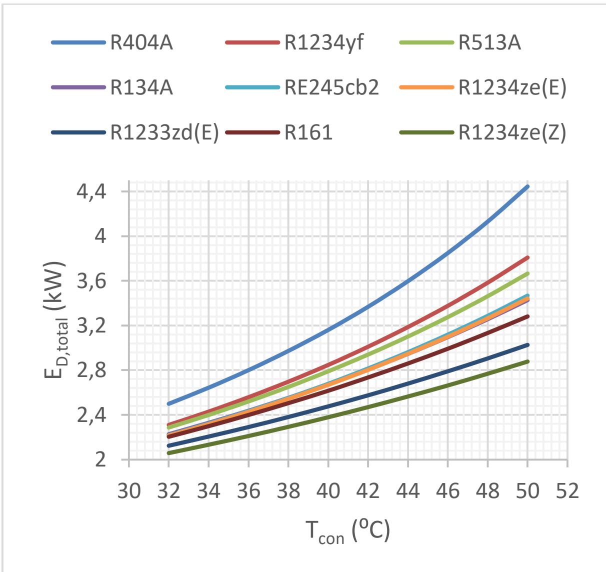

Figure 17. *Variation of the $E_{D,total}$ with the condenser temperatures of the refrigerants*

temperatures is shown from Figure 18 to Figure 21. Figure 18 shows that the highest exergy destruction values belong to R-404A, followed by R-161 and R-1234zd(E) in the evaporator. The lowest values have been obtained for R-1234ze(Z). The highest exergy and the lowest destruction values in the condenser belong to R-404A and R-1234zd(E), respectively (Figure 19). As the condenser temperature increases, the exergy destruction values in the

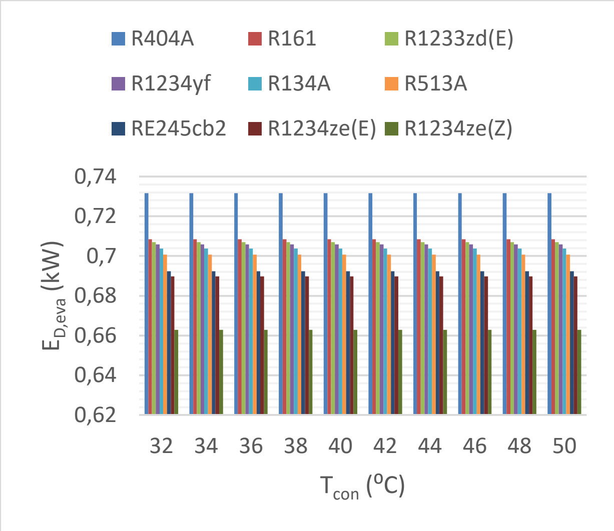

Figure 18. *Variation of the $E_{D,eva}$ with the condenser temperatures of the refrigerants.*

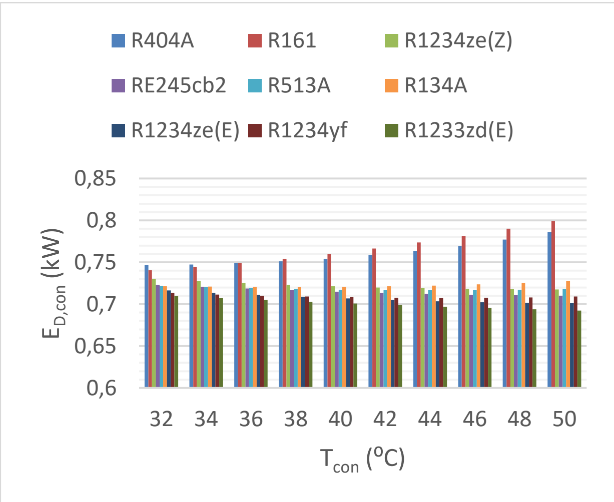

Figure 19. *Variation of the $E_{D,con}$ with the condenser temperatures of the refrigerants.*

compressor also increase. (Figure 20). In Figure 20, it is seen that the highest exergy destruction values in the compressor belong to the R-404A refrigerant. The other highest exergy destruction values belong to R-1234yf and R-513A refrigerants, respectively. On the other hand, the lowest exergy destruction values have been obtained for R-1233ze(Z). It shows that the highest and the lowest exergy destruction values in the hrottling valve were obtained in R-404A and R-1233ze(Z), respectively (Figure 21).

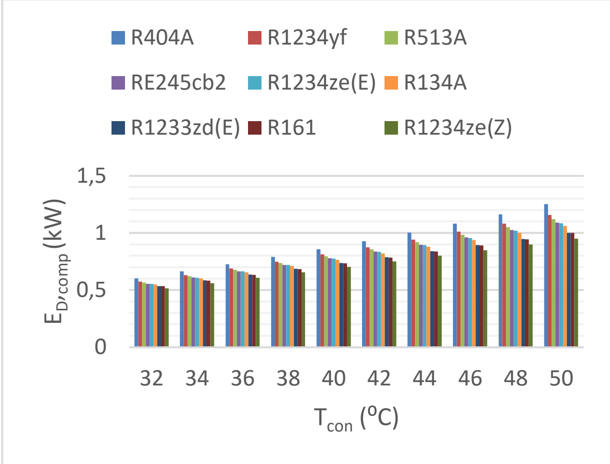

Figure 20. *Variation of the $E_{D,comp}$ with the condenser temperatures of the refrigerants.*

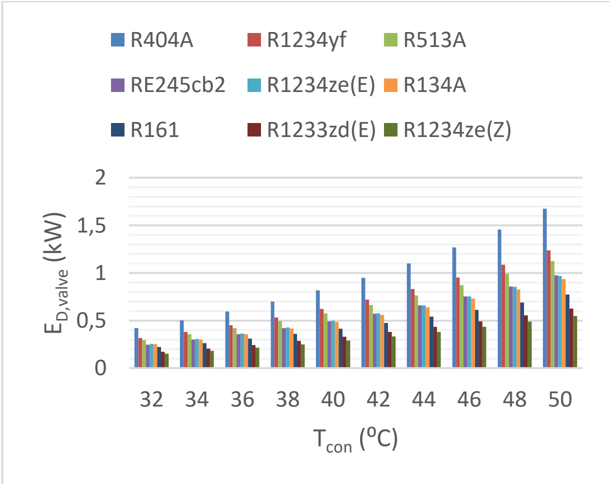

Figure 21. *Variation of the $E_{D,valve}$ with the condenser temperatures of the refrigerants.*

4. Conclusions

The air conditioning system used in vehicles needs energy to operate. The energy source used in vehicles is fuel. Chemical energy is converted into mechanical work by burning fuel in the vehicle engine. Again, the alternator in the vehicle generates electrical energy with the mechanical drive it receives from the engine. All systems and elements in the vehicle consume mechanical or electrical energy during their operation. The place with the highest energy consumption in the air conditioning system is the compressors. Power consumption values must be determined in order to determine the net effect of the compressor in the air conditioning system on the engine. The refrigerants used in the air conditioning system also have a decisive effect on the efficient and effective operation of the air conditioning system. In this study, detailed thermodynamic analyses of different refrigerants has been carried out in order to increase the performance of an air conditioning system operating according to the vapor compression refrigeration cycle in vehicles. For refrigerants selected as R-134A, R-E245cb2, R-404A, R-1234ze(Z), R-161, R-1234zd(E), R-513A, R-1234ze(E) and R-1234yf, detailed analyses have been made according to the first and the second laws of thermodynamics for different evaporator and condenser temperatures. In the study, the comparison has been made by taking account the safety, the environment and the performance values of the refrigerants.

In the analysis it was understood that for different evaporator temperatures, the highest COP value belongs to the R-1234ze(Z) refrigerant, followed by R-1234zd(E) and R-161 refrigerants, respectively. It has been observed that the lowest COP value belonged to the R-404A refrigerant. It is seen that the COP values decrease as the condenser temperatures increase. Among the analyzed refrigerants, the highest COP value belonged to R-1234ze(Z) refrigerant, while the lowest COP value belonged to R-404A refrigerant.

In the study, the second law efficiency values of the analyzed refrigerants have been calculated for different evaporator temperatures. It has been observed that the highest second efficiency value belonged to the R-1234ze(Z) refrigerant, while the lowest efficiency value belonged to the R-404A refrigerant. The exergy efficiency of all refrigerants decreases with the increasing of the condenser temperature. At increasing the condenser temperatures, the highest second law efficiency value belongs to R-1234ze(Z) refrigerant, while the lowest efficiency value belongs to R-404A refrigerant.

Total exergy destruction is very important in exergy analysis as it provides information about the energy quality degradation. The aim of the detailed exergy analyses in this study is to improve the cycle performance by finding exactly where the actual losses occur and how these losses can be reduced. In the analyses made for different evaporator temperatures, the highest exergy destruction values have been obtained for R-404A, while the lowest values have been obtained for R-1234ze(Z) according to the total exergy destruction values of the system. The highest exergy destruction values at increasing the condenser temperatures belong to R-404A, R-1234yf and R-513A refrigerants, respectively. It is seen that the lowest exergy destruction belongs to the R-1234ze(Z) refrigerant.

Among these refrigerants, R-1233ze(Z) has been found to be the best refrigerant compared to other refrigerants according to the environmental and the safety data. However, due to the flammability of these refrigerants, the necessary safety precautions are needed. The same is true for the R-1234ze(E) and the R-1234yf refrigerant. Although the ODP value of the R-E245cb2 refrigerant is zero, its GWP value is high. Although the ODP values of R-404A, R-134A and R-513A refrigerants are zero, they have high GWP values, which is the biggest disadvantage of these refrigerants.

The compressor, which is one of the main components of the air conditioning system, is driven by a pulley connected to the engine, which puts an additional load on the engine and therefore increases fuel consumption. The selection of the refrigerants with good performance, environmental and safety features in the vapor compression cooling system will make vehicles even more advantageous. As a result of the increasing the efficiency of the air conditioners, the size of the components used in the system can be reduced and the fuel consumption can be decreased.

Author Statements:

- The authors declare that they have equal right on this paper.
- The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- The authors declare that they have nobody or no-company to acknowledge.

Nomenclature

BACS	Bus Air Conditioning System
COP	Coefficient of performance
e	specific exergy (kJ kg^{-1})
E	exergy flow rate (kW)
h	enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (kPa)
$\dot{Q}$	heat flow rate (kW)
s	specific entropy (kJ kg-1 K-1)
T	temperature (K or ^oC)
$\dot{W}$	compressor work (kW)

Greek Letters

η	efficiency

Subscripts

com	compressor
con	condenser
eva	evaporator
D	exergy destruction
in	inlet
o	ambient
total	total system

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