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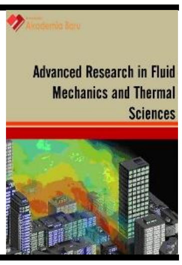

Energy-Exergy Analysis of Multistage Refrigeration System and Flash Gas Intercooler Working with Ozone-Friendly Alternative Refrigerants to R134a

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ARTICLE INFO	ABSTRACT

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Energy and exergy analysis were carried out for ten TR multistage vapour compression cycles and a flash gas intercooler, with alternative refrigerants to R134a, namely R1234yf, R1234ze, R245fa, and R227ea. The condensing temperature varied from 40 to 50°C, while the evaporator temperature remained constant at -10°C. The irreversibility analysis shows that the highest irreversibility among all system components occurred with the compressor and then the expansion valve, flash tank, and condenser, while the evaporator had the lowest irreversibility among all components. The system with R245fa had the lowest exergy destruction, highest exergetic efficiency, and highest COP when compared with other refrigerants. Therefore, this refrigerant is a viable alternative refrigerant to R134a.

Keywords:
multistage compression; alternative refrigerant; R134a

1. Introduction

The food preservation process requires a very low storage temperature below −10°C. The Iraqi summer climate has an ambient air temperature ranging from 45 to 50°C . For these conditions, the refrigeration system should operate with a condensation temperature ranging from 40 to 50°C [1]. A refrigeration system working with low temperatures (low suction pressure) requires large compressor displacement volume (large specific volume at inlet less mass flow rate), and with a high condensation temperature (high discharge pressure), this means the higher the compression ratio, the more the compressor must work. For these reasons, single stages cannot overcome this required condition, so a multistage compression process has been applied to provide more efficient operation conditions and prevent the compressor high-pressure ratio and high compressor capacity. The climate is suffering from global warming and ozone destruction, so many international unions recommend reducing this effect by increasing the system efficiency and replacing the current

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refrigerants with others that are ozone friendly and have a low global warming effect [16]. There are many studies on the multistage process, with many alternative refrigerants. Nikolaidis *et al.,* [10] Performed exergy analysis for a two-stage vapour compression cycle with flash intercooler. They found that the irreversibility of the condenser represents 41.6% of the plant, where evaporator irreversibility represents 34.8% of the plant. Ahmed Ouadha *et al.,* [2] Conducted exergy analysis for a multistage vapour compression cycle working with R290 and R717 as alternative refrigerants to R22. They found that the greater exergy extraction was accrued in the compressor. They predicted that the optimum inter-stage pressure for a two-stage refrigeration system would be equal to the saturation pressure corresponding to the arithmetical mean of the refrigerant condensation and evaporation temperatures. Therefore, the highest exergy destruction would be accrued in the condenser. Zhao *et al.,* [21] Conducted an experimental study comparison for a two-stage scroll compressor with flash intercooler and sub cooler. They found that the heating capacity of the system with the flash tank was more than the capacity of the system of the sub cooler. Therefore, the COP of the system with the flash tank was more than the COP of the system with the sub cooler under the same conditions. kilic [8] Performed an exergy analyses for a two-stage vapor compression refrigeration cycle with intercooler using refrigerants R507, R407c, and R404a. He found that at varying condensing temperatures, the evaporator had the highest irreversibility for all tested refrigerants, so the refrigerant R407C had the highest exegetic efficiency, while the system with R507 had the lowest among all adopted refrigerants. Kilicarslan [3] Conducted an exergy analysis for a simple vapour compression cycle working with refrigerants R290, R717, R718, and R744. He found that irreversibility

decreased as the evaporator temperature increased. Therefore, the condenser had the highest component irreversibility, while the evaporator had the lowest component irreversibility. R717 had the maximum exergetic efficiency, while R744 had the lowest. Kilicarslan *et al.,* [5] Conducted a theoretical study for a cascade refrigeration system with many refrigerants couples. They found that as the irreversibility decreased, the COP of the system increased, so the opposite was true. In addition, they found that the refrigerants couple R717-R23 had the highest COP with the lowest irreversibility from among the tested refrigerants, while the couple R507-R23 had the lowest COP and highest irreversibility. Bolaji et.al [9] Examined the exergetic performance of a refrigerator using R12, R134a, and R152a. They found that the COP of R152a was more similar to that of R12, and R134a had the highest efficiency defects. Vijay *et al.,* [17] Performed a comparison study between R12, R134a, and R1234yf and found that the system with R123yf had higher COP. Therefore, R1234yf was the best low global warming alternative refrigerant. Mastani *et al.,* [14] Performed exergy analysis for a refrigerator using R134a and R600a. They found that the compressor had the maximum value of destructed exergy. Saravanakumar *et al.,* [19] Tested the performance of a refrigerator by using a R134a and R290/R600a mixture. They found that the mixture of R290/R600a obtained COP and exergetic efficiency of more than R134a, while the compressor had the maximum irreversibility of the cycle. Kapil *et al.,* [13] Conducted exergy analysis for a two-stage vapor compression cycle working with R152a, R600, R600a, R410a, R290, R1234yf, R404a, and R134a. They found that the exergy efficiency of R134a was lower than that of R152a and R600. They observed that irreversibility was lower at higher evaporating temperatures, and the highest percentage of irreversibility was given by the condenser. Sertac *et al.,* [20] Performed a second-law analysis for a two-stage vapour compression refrigeration cycle with refrigerants R600, R290, R152a, and R141b. They found that the irreversibility of the components increased as the condenser temperatures increased, and the irreversibility of the components decreased as the evaporator temperature increased. The flash tank represented the lowest irreversibility component values, so the system working with R141b had the total lowest irreversibility value. Alsayyab [5] Conducted an exergy-energy comparison for a single-stage refrigeration system for many refrigerants as alternative refrigerants to R134a. The study showed that the refrigerant R227ea had the lowest exergy destruction and highest exergy efficiency from all investigated refrigerants. Ali [6] Conducted an experimental study of an exergy-energy comparison for an alternative refrigerant mixture for R134a. The results showed that the Mix2 refrigerant (70%R134a,10%R290, 20%R600a) was the best among other proven refrigerants as an alternative refrigerant to R134a, with COP reduction of 8.18% and Global Warming Potential (GWP) of 910.9. Mohammed *et al.,* [15] Performed an exergy-energy comparison for a refrigeration system working with different refrigerants as alternatives to R22. The results of the study showed that the refrigerant R290 and R1270 exhibited identical exergy efficiency behaviour and R22 had lower exergy efficiency, while R600a and R600 had the highest exergy efficiency in comparison to R22. Ali k. [22] Carried out an experimental study on the performance of window-type air-conditioning by adding a diffuser at the compressor outlet. The study showed that using a diffuser of 5mm ID, 9mm OD and 12mm L in an air-conditioning system will increase COP by 29% from the base case. Sani *et al.,* [23] study the noise level of split unit air conditioner, they found that the highest noise level was occurs at the front side of air conditioner.

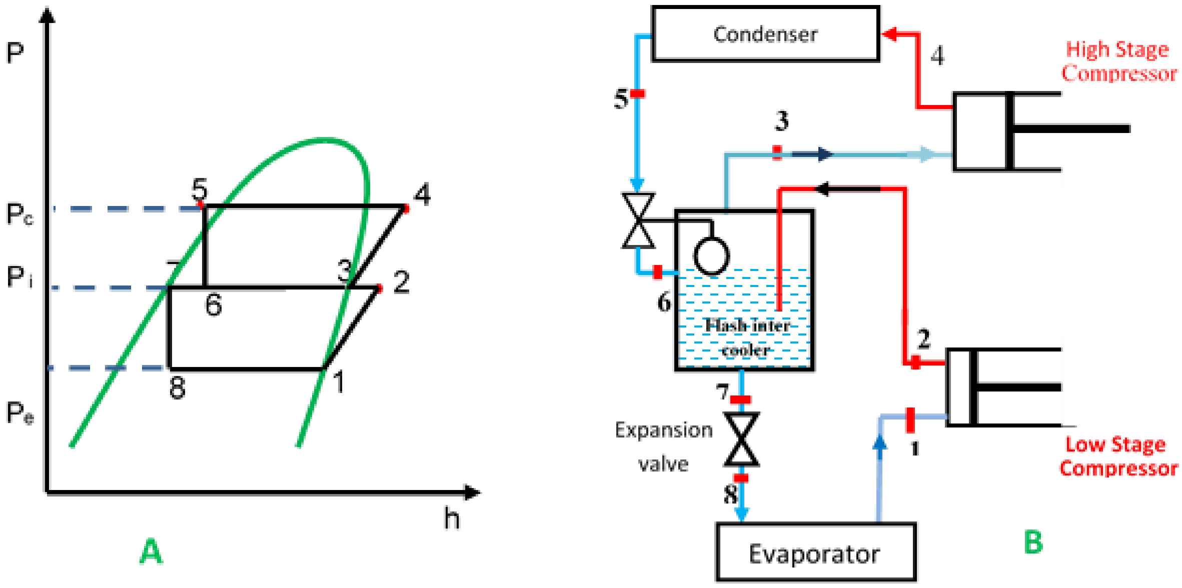
The current study conducted an exergy-energy analysis for a multistage vapour compression cycle of 10 TR with ozone-friendly alternative refrigerants to R134a, namely R1234yf, R1234ze, R245fa, and R227ea. Table 1 shows the thermodynamic properties for these refrigerants compared to R134a.

Table 1
Properties of studied refrigerants [4]

Refrigerant	R 134a	R227ea	R245fa	R1234yf	R1234ze
Critical temperature in °C	101	102.8	154	94.7	109.4
Critical pressure (bar)	42.4	29.99	36.51	33.82	36.32
Molecular weight kg/kmol	102	86.05	87.46	75.87	81.66
Boiling point in °C at 1.0135 bar	-26.5	-16.25	15.9	-29.48	-19.27
Vapour-specific volume m^3/kg	0.1925	0.1197	0.1678	0.1677	0.1739
h_{fg} at -25 °C kJ/kg	216.3	135.5	217.7	178.3	199.5
GWP 100 years	1300	3330	930	<1	<1
Ozone Depletion Potential (ODP)	0	0	0	0	0

2. Multistage Vapour Compression Cycle with Flash Intercooler

The cycle components are shown in Figure 1(b), which includes a low-stage compressor, high-stage compressor, condenser, flash tank, and expansion valve. In this cycle, the flash tank acts as intercooler and flash gas remover by passing all liquid refrigerant through the float valve of the tank. The super-heated refrigerant from the low stage always enters the flash tank in such a way below the refrigerant level in the tank. The heat rejected from the wet refrigerant and the heat of the super-heated refrigerant that are delivered to the tank from the low stage make some portion of the refrigerant wet before boiling (when the liquid refrigerant passes through the float valve, some of the refrigerant is flashed and the liquid refrigerant becomes wet). The saturated vapour of the boiling refrigerant accumulates in the top of the tank, and as a result, the wet refrigerant becomes liquid refrigerant due to rejected heat. The saturated liquid refrigerant is drawn from the bottom of the tank, passes through the expansion valve, and is delivered to the evaporator [18].



(a) P-h representation (b) Block diagram

Fig. 1. Multistage vapour compression cycle with flash inter cooler

3. Thermodynamic Analysis

Energy balance

For low-stage compressor

$$w_{LP} = h_2 - h_1 \quad (1)$$

$$Power_{LP} = \dot{m}_1 * (h_2 - h_1) \quad (2)$$

For high-stage compressor

$$w_{HP} = h_4 - h_3 \quad (3)$$

$$Power_{HP} = \dot{m}_4 * (h_4 - h_3) \quad (4)$$

Heat rejected by condenser

$$Q_c = \dot{m}_4 * (h_4 - h_5) \quad (5)$$

Refrigerating effect

$$qe = h_1 - h_9 \quad (6)$$

Refrigeration capacity

$$RC = \dot{m}_1 * (h_1 - h_8) \quad (7)$$

$$\text{Coefficient of performance COP} = \frac{\text{Refrigeration capacity}}{\text{Power}} \quad (8)$$

Exergy analysis

The exergy destruction in the cycle occurred in the compression process, condensing process, expansion process, cooling in the flash tank, and evaporation process. The exergy destruction for cycle components can be determined by [11]

For low and high compressors

$$EX_{Destc\_Com}=T_o\,[(m_2\,(s_2-s_1)+m_3\,(s_4-s_3)] \quad (9)$$

For condenser

$$EX_{Destc\_Con}=m_3\,[(h_4-h_5+T_o\,(s_5-s_4)-qc\,(1-\frac{To}{Tc})] \quad (10)$$

For expansion valve

$$EX_{Destc\_Ex}=T_o\,[m_3\,(s_6-s_5)+m_7\,(s_8-s_7)] \quad (11)$$

For flash tank

$$ED_{Destc\_FT}=m_3\,[(h_3-h_6)-T_O\,(s_3-s_6)]-m_2\,[(h_2-h_7)-T_O\,(s_2-s_7)] \quad (12)$$

For evaporator

$$EX_{Destc\_Ev}=m_2[h_1-h_8-T_o\,(s1-s8)-re\,(1-\frac{To}{Te})] \quad (13)$$

Total exergy destruction

$$EX\_{_T}=EX_{Destc\_Com}+EX_{Destc\,\_Con}+EX_{Destc\,\_Ex}+EX_{Destc\,\_Ev}+EX_{Destc\_FT} \quad (14)$$

$$\eta_{exergy}=1-\frac{EX\_T}{wT} \quad (15)$$

$$\text{Sustainability index}=1-\frac{1}{\eta_{exergy}} \quad (16)$$

4. Results and Discussion
4.1 Effect of Condensing Temperature
4.1.1 Compressor consumption power and exergy destruction

The compressor performance for the selective refrigerant is shown in Figure 2. It is clear that at a constant evaporation temperature, as the condensation temperature increased, the compressor consumption power increased due to the increase in pressure ratio, which reduced the required refrigerant mass flowrate and increased the irreversibility, as shown in Figure 3. The system of refrigerant R227a had the highest compressor consumption power and exergy destruction, while R245fa had the lowest compressor consumption power and exergy destruction. This means that the irreversibility increased the consumption power.

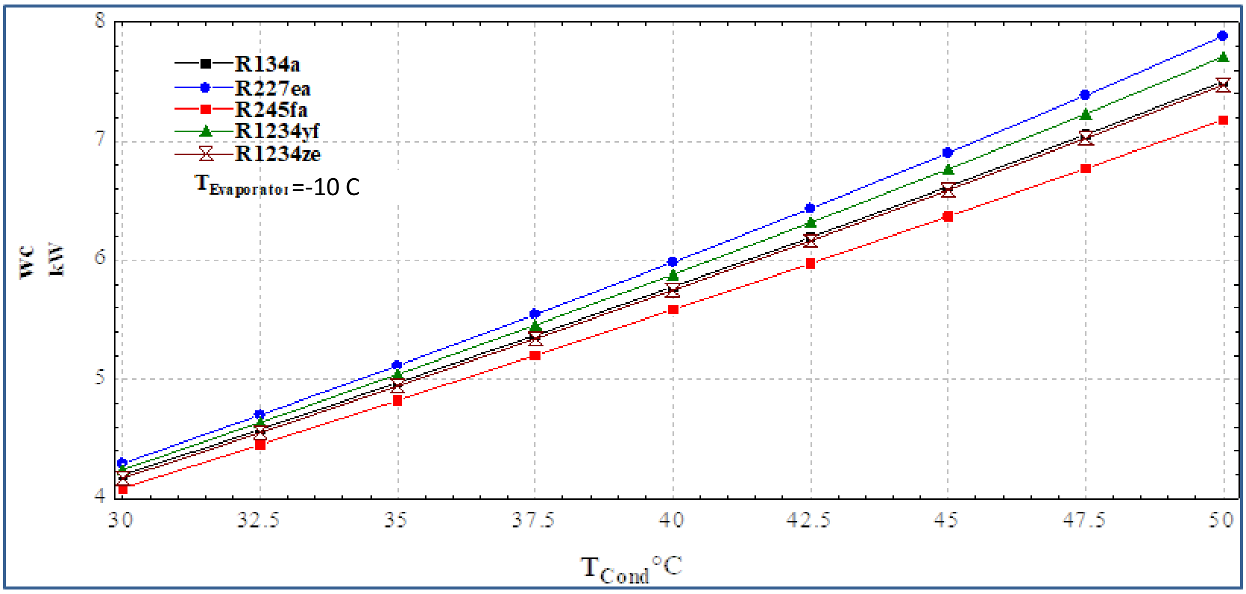


Fig. 2. Effect on condensing temperature on compressor power

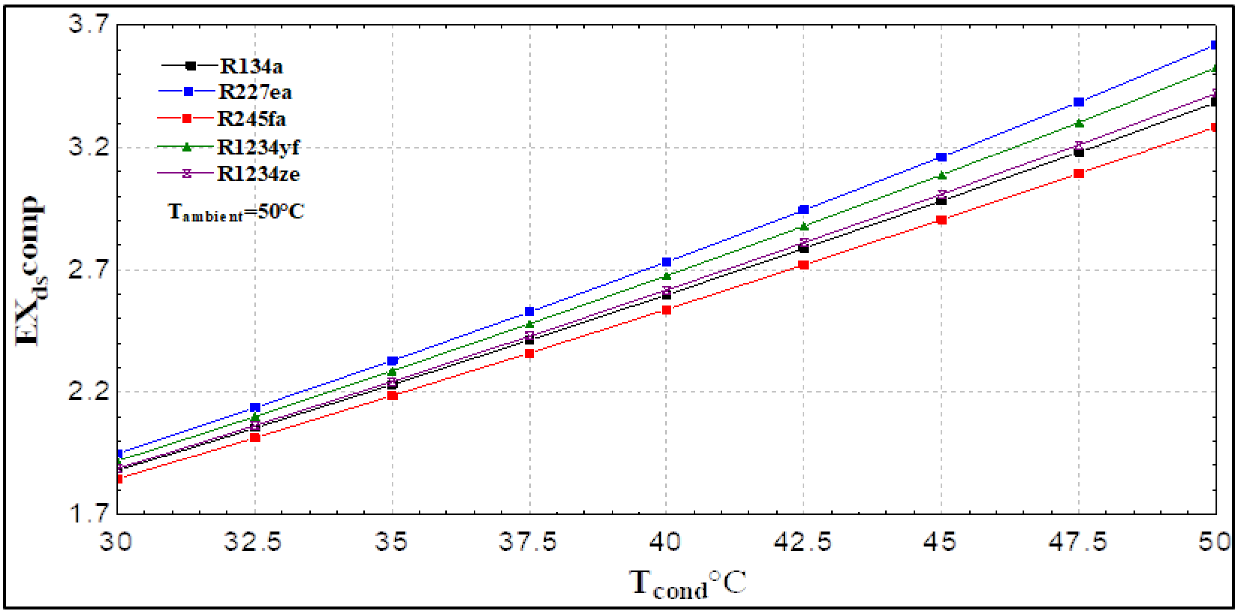


Fig. 3. Effect of condensing temperature on compressor exergy destruction

4.1.2 Condenser heat rejection and exergy destruction

The condenser performance is shown in Figure 4. As the condensation temperature increased, the latent heat of condensation decreased, so the refrigerant mass flow rate delivered by compressor decreased due to the reduction in compressor volumetric efficiency. Consequently, condenser heat rejection decreased as the condensing temperature increased. The refrigerant R245fa had the highest condenser heat rejection among all selective refrigerants, and R227ea had the lowest value.

Figure 5 indicates that as the condensing temperature increased, the condenser exergy destruction increased due to the increase in the refrigerant-to-air temperature difference. The refrigerant R245fa had the lowest condenser exergy destruction among all selective refrigerants.

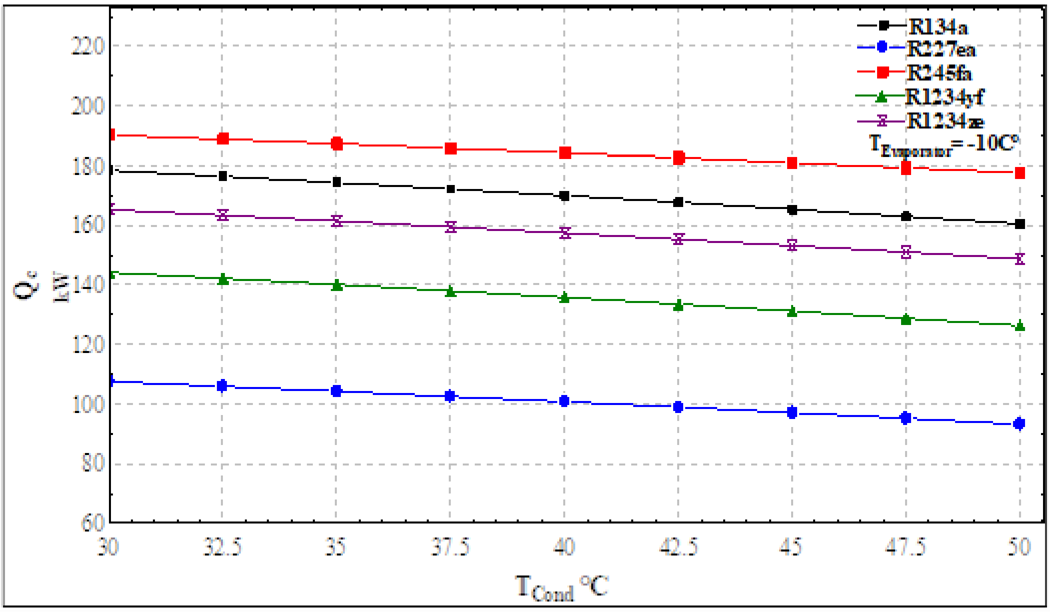


Fig. 4. Effect of condensation temperature on condenser heat rejection

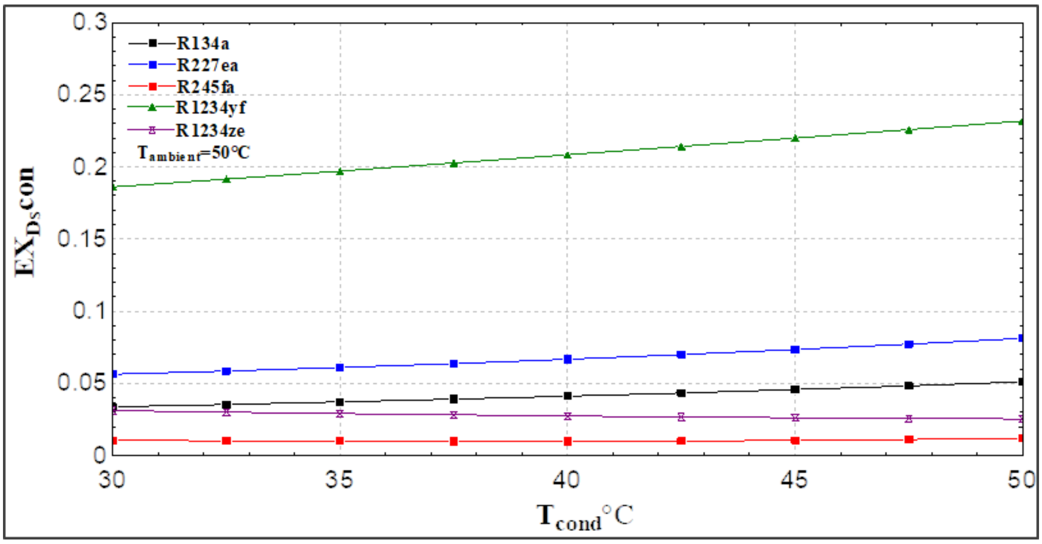


Fig. 5. Effect of condensation temperature on condenser exergy destruction

4.1.3 Expansion valve and flash tank exergy destruction

Figure 6 illustrates the exergy destruction through the flash tank and expansion valve. The exergy destruction increased as the condensing temperature increased, due to the increase in the refrigerant-to-ambient air temperature difference that increased the irreversibility. The system with refrigerant R227ea had the highest flash tank–expansion valve exergy destruction, while R134a showed the lowest flash tank exergy destruction among all selective refrigerants.

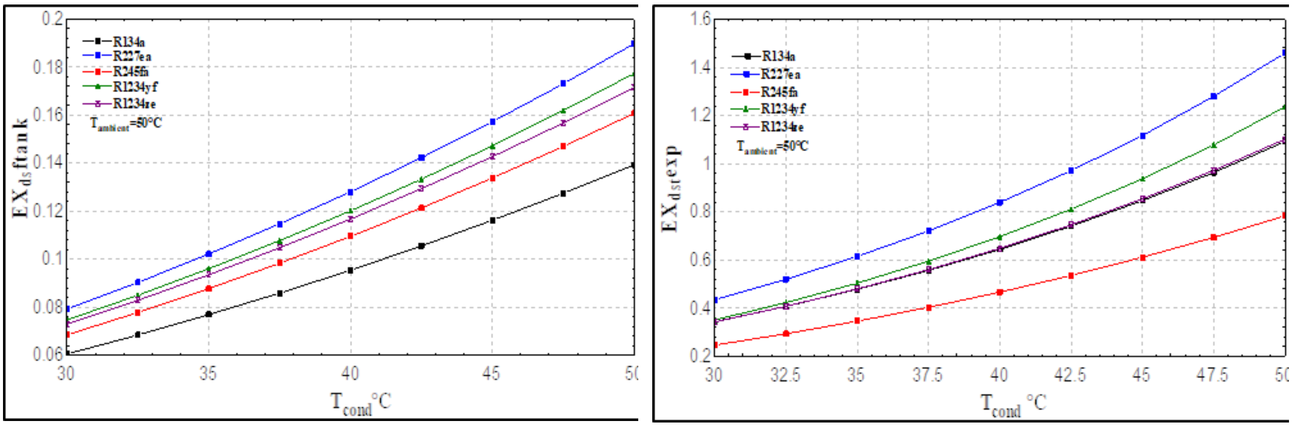


Fig. 6. Effect of condensation temperature on exergy destruction of flash tank, expansion valve

4.1.4 Evaporator heat absorbing and exergy destruction

At a constant evaporator temperature and degree of super heating, the evaporator heat absorbed decreased slightly as the condensing temperature increased, as seen in Figure 7. This is because the flash tank provided liquid only to the evaporator, and the condensing temperature increasing had little effect on the flash tank liquid level and only affected flash tank pressure (the dryness fraction at the evaporator inlet was relatively constant). Consequently, the variation in condensing temperature had little effect on the heat absorbed by the evaporator, leading to the exergy destruction, as seen in Figure 8. The system with R245fa had the highest heat absorbed and lowest evaporator exergy destruction among all selective refrigerants.

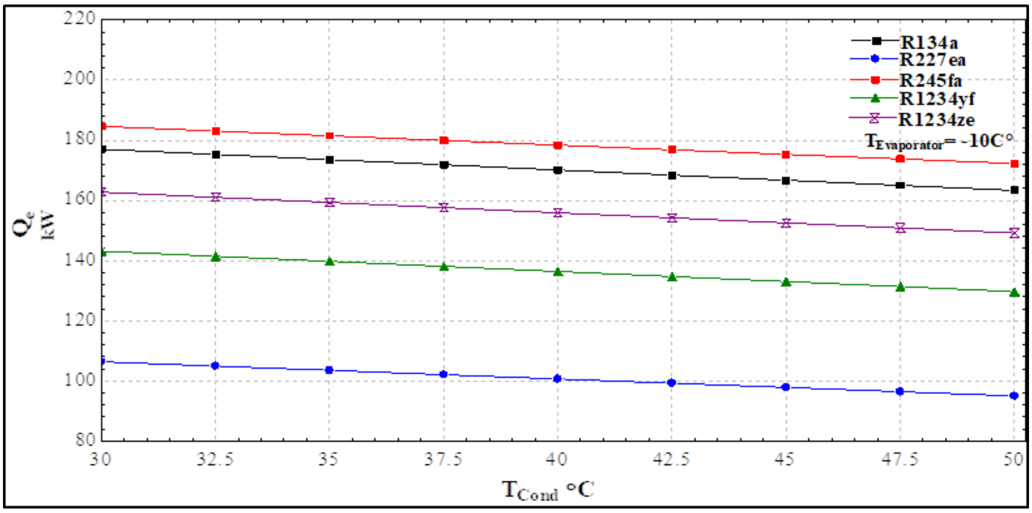


Fig. 7. Effect of condensation temperature on evaporator heat absorbed

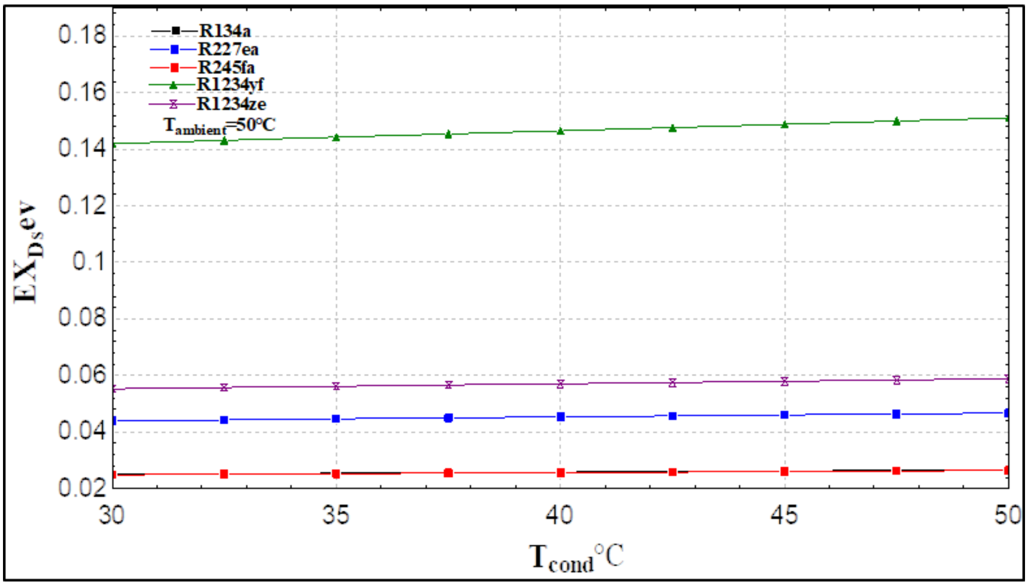


Fig. 8. Effect of condensation temperature on evaporator exergy destruction

4.1.5 Coefficient of performance (COP) and exergetic efficiency

COP is the ratio of evaporator capacity to compressor power. As discussed in the compressor and evaporator paragraphs, as the results of the condensing temperature increased, the consumption power increased, while the evaporator heat absorbed decreased, so that both the compressor and evaporator irreversibility increased. Consequently, COP decreased as the condensing temperature increased, as seen in Figure 9.

The system exergy destruction increased due to the irreversibility increasing among all system components, as seen in Figure 3, and as a result of the condensing temperature increasing, the consumption power increased. Consequently, the system exergetic efficiency decreased as the condensing temperature increased, as demonstrated in Figure 10. The system with R245fa had the lowest total exergy destruction, highest exergetic efficiency, and highest COP among all tested refrigerants.

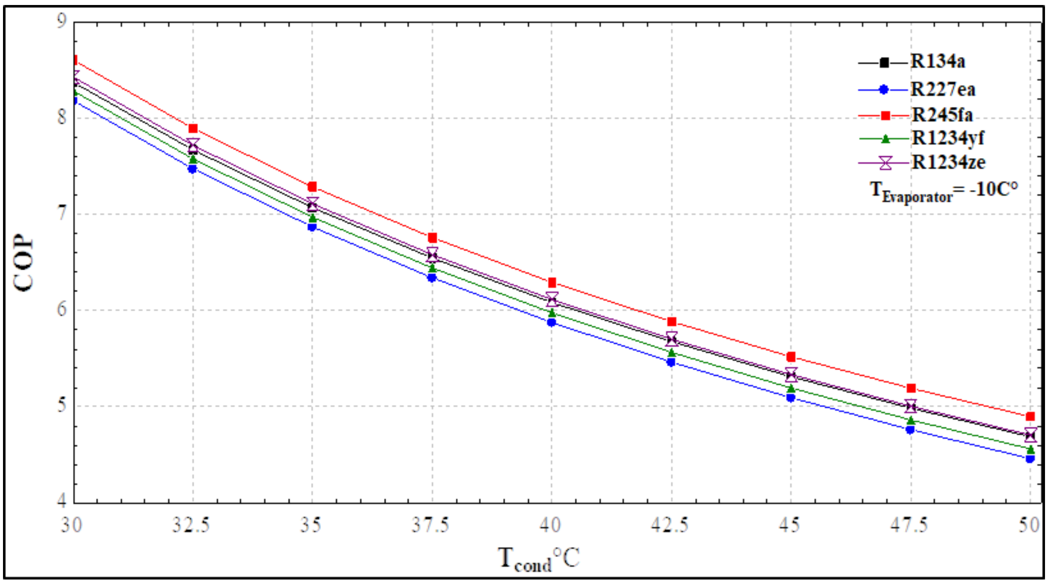


Fig. 9. Effect of condensation temperature on COP

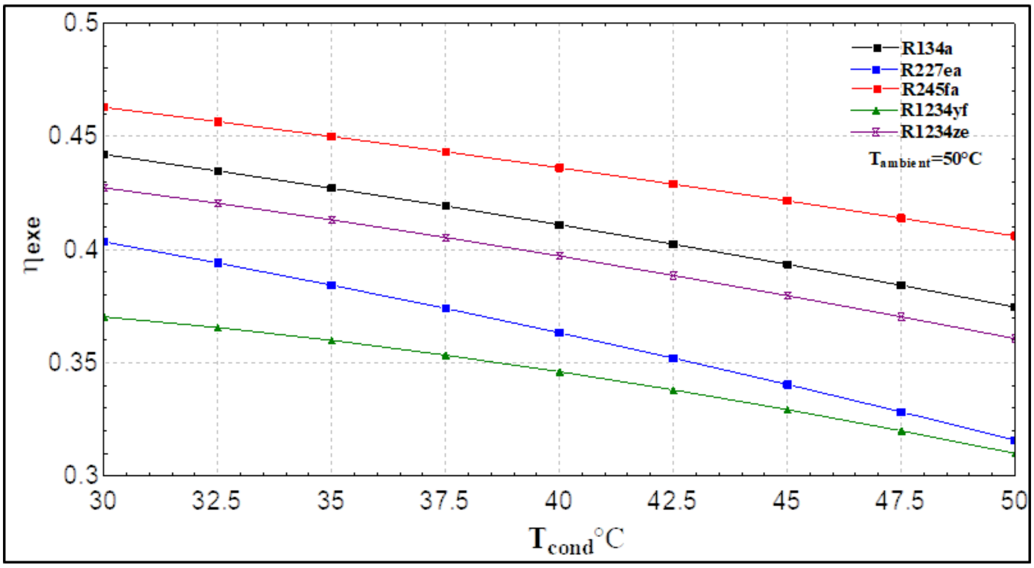


Fig. 10. Effect of condensation temperature on exergy efficiency

5. Conclusions

The increase in condensing temperature reduced the volumetric efficiency, so the refrigerant mass flowrate delivered by the compressor increased the compressor work and decreased the condenser heat rejection. Consequently, this reduced the COP of the system. At a constant evaporator temperature, the compressor had the highest irreversibility among all system components, while evaporator had the lowest irreversibility among all system components. The system with R245fa had the lowest exergy destruction, highest exergetic efficiency, and highest COP when compared with other refrigerants. Therefore, it can be selected as an alternative refrigerant to R134a. The refrigerant R1234yf showed the highest exergy destruction, lowest exergetic efficiency, and lowest COP. The varying condensing temperature had little effect on the evaporator heat absorbed among all tested refrigerants.

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