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Review Article

R1234yf and R744 as alternatives to R134a at mobile air conditioners

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Abstract: R1234yf is a synthetic HFO refrigerant co-developed as a replacement refrigerant for R134a in automotive air conditioning applications. Thus, in this study, alternatives to the R134a refrigerant that were removed from the newly produced devices were examined. The performance of the cooling processes of R1234yf and R744 refrigerant gases was compared with that of R134a. A simulation model was first developed. This simulation model was validated with experimental results. Analysis was conducted for both cooling and heating modes. In the case of cooling, evaporation temperature was 5 °C–7.5 °C, condenser, or gas cooler outlet temperature was 35 °C–50 °C and the cooling load was 10 kW. In heating mode, evaporation temperature was −4 °C–12 °C, condenser, or gas cooler outlet temperature was 45 °C–50 °C and the heating load was 13.5 kW. The results were analyzed in terms of the coefficient of performance (COP), compressor power consumption, and compressor discharge temperature. In terms of COP and compressor power consumption, R134a gave the best results in all cases. R1234yf gave the closest results to R134a. In terms of compressor discharge temperature, which affects the lifetime and lubrication quality of the compressor, R1234yf gave the lowest temperatures in all cases.

Keywords: *Air conditioning, COP, Energy efficiency, Refrigerant, R134a,*

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Nomenclature	
C	Cooling mode
comp	Compressor
cond	Condenser
COP	Coefficient of Performance
cr	Critical
evap, e	Evaporator
Exp	Experimental
gc	Gas cooler
gco	Gas cooler outlet
h	Enthalpy (kJ/kg)
H	Heating mode
K	Melting
m	mass
P	Pressure (bar)
Q	Heat (kW)
ref	Refrigerant
Sim	Simulation
T	Temperature (ºC)
W, w	Work (kW, kJ/kg)

1. INTRODUCTION

At the beginning of the 20th century, carbon dioxide, the most used refrigerant along with ammonia, began to be not preferred in air conditioning applications with the emergence of Chlorofluorocarbons (CFCs). Despite being the most known greenhouse gas, the global warming potential (GWP) of R744 is much less than CFCs and Hydrofluorocarbons (HFCs). So, because of the increased environmental sensitivity, it has been taken into consideration by the refrigeration industry and viewed as an alternative to R134a. European Union Mobile Climate Regulation [1] of May 17, 2006, was declared in 2006 and was enacted as of July 4, 2008. R1234yf has been developed to take the place of R744 (CO_2) as an alternative to R134a. In mobile climate applications, R744 and R1234yf have come to the forefront in vehicle-cooling systems.

R1234yf refrigerant has been developed to replace R134a in mobile climate applications. R1234yf has excellent environmental characteristics, which can be seen in Table 1 [2]. Chen et al. [3] showed that it has similar performance characteristics to R134a by evaluating the current state in China. Some experimental studies compared using these two refrigerants in mobile air conditioners. Zhao et al. [4] stated that the cooling capacity and COP of the R134a system were 12.4% and 9% greater, respectively. And the performance of the system using R1234yf can be increased by redesigning the expansion valve, using more efficient heat exchangers, and adding internal heat exchangers to the system. Navarro-Esbrí et al. [5] added an internal heat exchanger (IHX) to a system and investigated it experimentally. Their results showed that before adding IHX, the cooling capacity and COP of the R1234yf cycle were 9% and 19% lower, respectively, compared to the R134a cycle. After adding IHX, these percentages decreased significantly. To determine this decrease, Cho et al. [6] performed performance tests using R1234yf and R134a in the same automotive cooling system. They showed that without IHX, cooling capacity and COP were lower up to 7% and 4.5%, respectively. But, with IHX, they decreased by up to 1.8% and 2.9%, respectively.

Table 1. Thermophysical and environmental specifications of R134a, R1234yf, and R744

Refrigerants	Weight (kg/kmol)	T_K (°C)	T_{cr} (°C)	P_{cr} (bar)	Ozone depletion potential	Global warming potential	Atmospheric Life (year)
R134a	102.03	−26.1	101.1	40.6	0	1430	14
R1234yf	114.04	−29.5	94.7	33.8	0	<4.4	29
R744	44.01	—	31	73.8	0	1	>50

Air conditioning units can also be used as heat pumps with proper modification. Aral et al. [7] developed an automotive air conditioning and heat pump system using R134a and R1234yf refrigerants. According to the results of the tests, the energy efficiency of the R1234yf system was on average 17.6% and 14.7% lower in cooling and heating modes compared to R134a, respectively. Based on these results, they stated that the use of R1234yf instead of R134a is not only suitable for air conditioners but also suitable for heat pumps.

High compressor outlet temperature causes lube oil degradation. Thus, this temperature should also be compared when performing drop-in tests. Besides stating that the COP and capacity of the system using R1234yf were as low as 2.7% and 4%, respectively, Lee and Jung [8] also stated that the compressor outlet temperature is 6.4 °C–6.7 °C lower than the system using R134a. Li et al. [9] investigated these temperatures, especially at electric mobile vehicles in cold climates. They stated that the compressor outlet temperature in the system using R1234yf is 2.5–3.5 °C lower than the R134a system, and these lower temperatures are beneficial for the compressor.

R1234yf is not the only replacement refrigerant alternative. There are some studies on other suitable refrigerants. Bolaji [10] theoretically studied R152a, R161, and R1234yf as alternative refrigerants for R134a in the vapor compression refrigeration system. According to the results obtained, R1234yf gave the lowest average performance coefficient by 7.1%. Vaghela [11] studied R290, R600a, R407C, R410A, R404A, R152a, and R1234yf that can be used in place of R134a for automobiles. As a result, R1234yf had a lower coefficient of performance compared to R134a. But they stated R1234yf is the most suitable alternative refrigerant since its global warming potential is low and it can be used with minimal modification in the existing automobile air conditioning system.

CO_2 (R744), whose thermophysical properties are shown in Table 1, is one of the priest refrigerants used in air conditioners. It is important in the system design that its critical point is low in temperature and high in pressure. Studies are investigating various effects in systems using R744 in the literature. Wang et al. [12] studied to reveal the effects of outdoor temperatures on the cooling performance of mobile air conditioners. They noted in their study that compared to a conventional R134a mobile air conditioning system, the COP of the CO_2 prototype decreased by 26% and 10% at 27 °C and 45 °C outdoor conditions, respectively. They emphasized that the increase in overall compressor efficiency or decrease in gas cooler approaching temperature would improve the COP of the system. Zheng et al [13] worked to achieve better scroll compressor performance for CO_2 in the heat pump air conditioning system. An unsteady Reynolds Average Navier-Stokes run process was performed on a transcritical CO_2 powered scroll compressor. The effect of CO_2 properties table resolution on numerical simulation has been studied. Their results provide an instrumental guide for the optimum design of the supercritical CO_2 scroll compressor.

In addition to the demand for performance improvement, one of the main reasons for replacing refrigerants is environmental effects. For this purpose, Yuan et al [14] developed a model for calculating the life cycle greenhouse gas emissions. They stated that using R1234yf as an alternative refrigerant instead of R134a in mobile vehicle air conditioning systems can reduce lifetime greenhouse gas emissions by 17%–29%. Zhiyi et al [15] determined the CO_2-equivalent emissions with different refrigerants. They stated that if R152a, R1234yf, and R744 are used respectively in mobile air conditioning systems, CO_2 equivalent emissions will only constitute 8.74%, 0.28%, and 0.07%.

Besides energy analysis, exergy analysis is an important method for evaluating the potential of systems. So, some studies have also focused on exergy analysis to compare the refrigerants. Golzari et al. [16] investigated the use of R1234yf instead of R134a in automobile cooling systems based on the second law of thermodynamics. They stated that the exergy efficiency of R1234yf is higher than R134a. Paula et al. [17] investigated the energetic and exergetic performance of R290, R1234yf, and R744 to replace R134a in a refrigeration system. At the end of the study, they showed that although R290 showed the best performance, R744 gave better results than R1234yf in terms of both COP and exergy efficiency.

When the literature is examined, it is seen that there are studies of different refrigerants working as subcritical and transcritical cycles at vapor compression refrigeration cycles. However, in this study, the simulation temperature range was redefined depending on the intended use and the performances of the refrigerants in the specified ranges were examined. Within the aim of this study, R1234yf and R744 refrigerants were tested to replace R134a in mobile vehicle air conditioners. For this purpose, a simulation model was developed and experimentally validated by the results of some experimental studies in the literature. The obtained results are examined at different evaporation and condenser or gas cooler outlet temperatures for both cooling and heating conditions.

2. METHODOLOGY

2.1. Model

To evaluate the performance of mobile vehicle air conditioning systems using different refrigerants, a vapor compression refrigeration cycle was created in the EES program. The R134a and R1234yf cycles are single-stage subcritical cycles.

Since the critical point temperature of carbon dioxide is relatively low (31 °C), a transcritical model was created for R744. Since there is no phase change above the critical point, the condenser in subcritical cycles is replaced by a gas cooler in transcritical cycles [18]. At pressures above the critical point, both pressure and temperature should be defined since the pressure and temperature of the refrigerant are independent of each other. The coefficient of performance of the cycle is variable at the same gas cooler outlet temperature, and different operating pressures. Therefore, the gas cooler used in the simulation model was operated at the optimum gas cooler pressure with Eq. (1) developed by Liao et al. [19].

$$P_{opt} = (2.788 - 0.0157t_e) \times t_{gc} + (0.381 \times t_e - 9.34) \quad (1)$$

The key components of the created cycles, along with their theories (Eqs. (2-4)), are given below.

1–2: Compressor compression

2–3: Heat transfer in the condenser or the gas cooler

3–4: Expansion in a thermostatic expansion valve

4–1: Evaporation in the evaporator

$$\dot{Q}_{cond} = \dot{m}_{ref} \times (h_3 - h_2) \quad (2)$$

$$\dot{Q}_{evap} = \dot{m}_{ref} \times (h_1 - h_4) \quad (3)$$

$$\dot{W}_{comp} = \dot{m}_{ref} \times (h_1 - h_2) \quad (4)$$

The performance of the system is calculated with the following equations in cooling (Eq. (5)) and heating (Eq. (6)) modes.

$$COP_C = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \quad (5)$$

$$COP_H = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \quad (6)$$

Compressor isentropic efficiencies are taken from the manufacturer's catalogs depending on the operating parameters. Pressure losses in the system have been neglected.

2.2. Validation

Some experimental studies in the literature were used to validate the created simulation model with experimental data. For this purpose, Jarall's work [20] was used for R134a and R1234yf. Jarall conducted a study on the use of R1234yf instead of R134a and shared the results in tables. In the experiments, the condenser outlet temperature was 40 °C–45 °C and the evaporation temperature was between −8 °C–15.5 °C.

The parameters in the experiments given in [20] were inputted into the simulation we created in this study. The results obtained are given in Figs. 1-4 compared with 15% error bars.

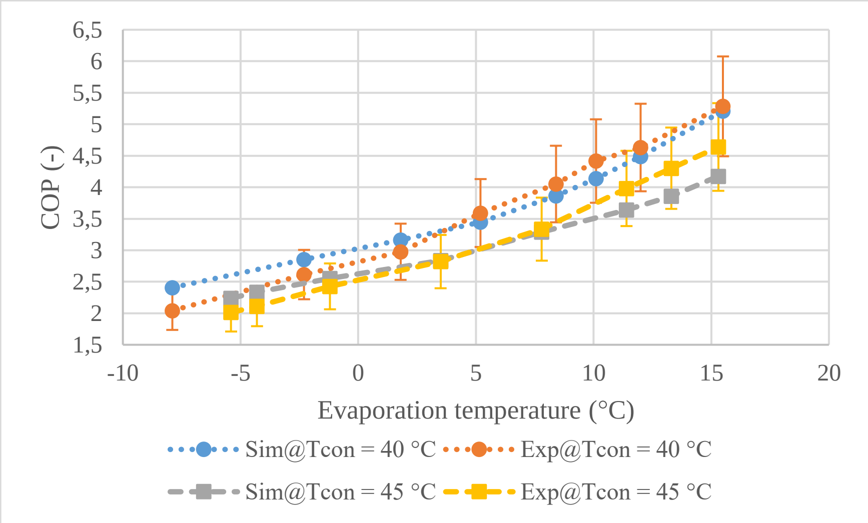

Figure 1. Comparison of experimental and simulation COP values based on evaporation and condensation temperature for R134a.

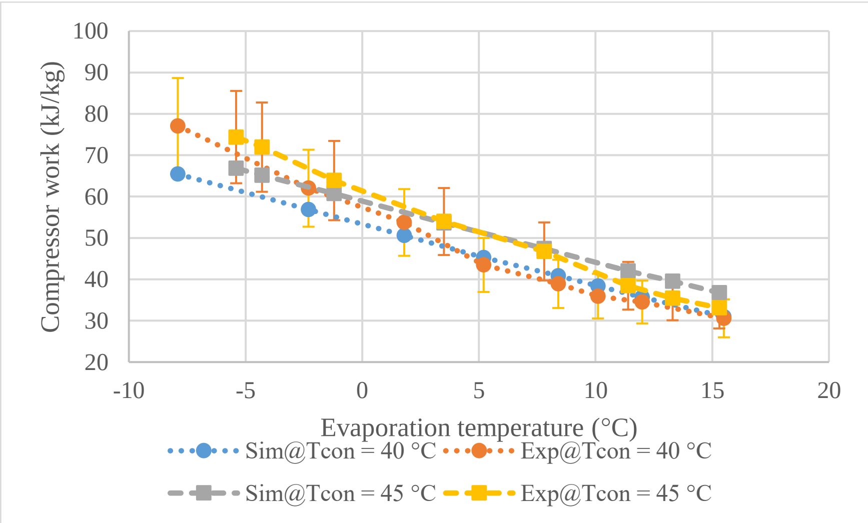

Figure 2. Comparison of experimental and simulation compressor consumption based on evaporation and condensation temperature for R134a.

To show the acceptability of the results, the relative errors between the experimental and the results of the simulation were calculated using Eq. (7).

$$\text{Relative Error (\%)} = \left|\frac{(Experimental\ Result\ -\ Simulation\ Result)}{Experimental\ Result}\right| \times 100 \qquad (7)$$

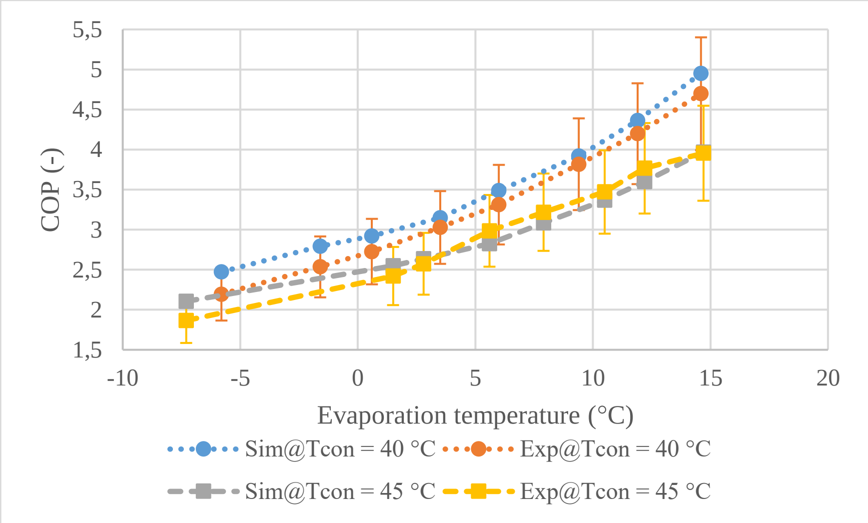

Figure 3. Comparison of experimental and simulation COP values based on evaporation and condensation temperature for R1234yf.

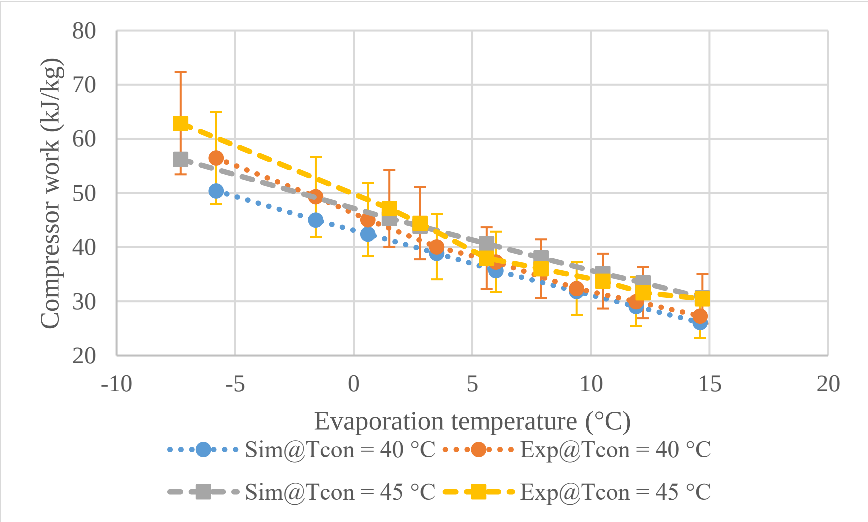

Figure 4. Comparison of experimental and simulation compressor consumption based on evaporation and condensation temperature for R1234yf.

Table 2 shows the mean relative error calculated from the results obtained depending on the condensation temperature.

Table 2. Mean relative errors between experiments and simulations

T_{con} (°C)	Mean Relative Error (%)			
	COP		w	
	R134a	R1234yf	R134a	R1234yf
40	6.6	6.4	6.2	5.3
45	7.3	4.7	7.3	4.9

When the obtained results are examined, it is seen that the results of the simulations are compatible with both R134a and R1234yf. Unlike Jaral's study, in our simulation study, the condensation temperature ranges were extended, and another refrigerant (R744) was also tested. All calculations were made for the heating and cooling season.

The papers of Klöcker et al. [21, 22] were used to validate the model with carbon dioxide as the refrigerant. They used an industrial heat pump dryer with R744 and conducted experiments. Only the refrigerant side of the results, which includes both the airside and the R744 side, was used within the aim of this study. These studies have been appropriately used for validation in the literature before [23, 24, 25]. The experimental and simulation results for the efficiency and compressor consumption of the heat pump system are given in Table 3.

Table 3. Comparison of experimental and simulation results for R744 cycle

COP (-)			Compressor Consumption (kW)		
Experimental	Simulation	Relative Error (%)	Experimental	Simulation	Relative Error (%)
6.5	5.9	8.6	1.85	2.02	9.1

The results obtained show that the model with R744 is also compatible with the experimental results.

3. RESULTS AND DISCUSSION

With the developed model, calculations for R134a, R1234yf, and R744 were made separately for 10 kW-cooling load and the findings were compared with each other. In the case of cooling, the condenser or gas cooler outlet temperature was selected as 35 °C–50 °C and the evaporation temperature was selected as 5 °C–7.5 °C. Also, calculations for these refrigerants were made for a 13.5 kW-heating load and the results were shown below. In the case of heating, the evaporation temperature was selected as −4 °C–12 °C and the condenser or gas cooler outlet temperature was selected as 45 °C–50 °C.

Fig. 5 shows the refrigerant cycles in the pressure-enthalpy diagram obtained from our simulation. In this figure, the system is operated in the heating mode with R134a. Evaporation temperature is 5 °C and condensation temperatures range from 35 °C to 50 °C.

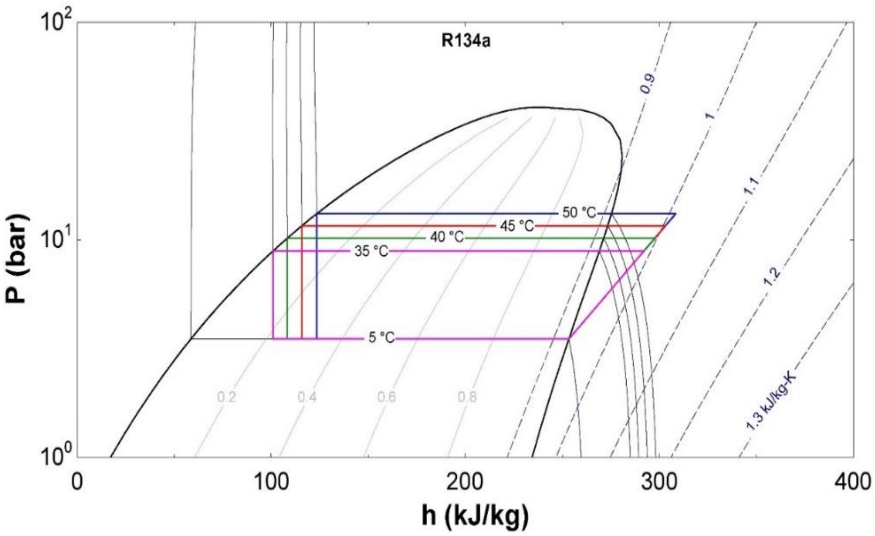

Figure 5. Heating mode refrigerant cycles for different condensation temperatures.

Fig. 6 shows the heating mode refrigerant cycles for R134a, R1234yf, and R744 in the same graph for 5 °C evaporation and 50 °C condensation temperatures on the same graph. The saturation curves of the three refrigerants, depending on the enthalpy and pressure values obtained from our simulation, were reduced to the same graph to compare the cycles only visually in the same operating conditions.

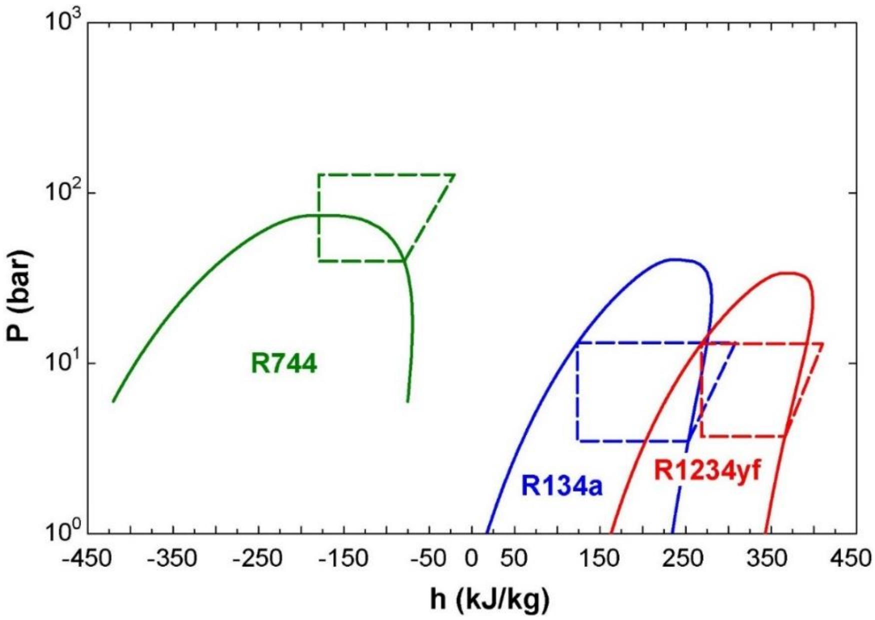

Figure 6. Heating mode refrigerant cycles for different refrigerants in the same operating parameters.

As can be seen from Fig. 7, at the same evaporation temperature the COP values of R134a and R1234yf are close to each other in the case of cooling, but the COP of R744 is slightly lower. Increasing the condenser or gas cooler outlet temperature in cooling mode requires more compression to a higher pressure in the compressor. This results in reduced cooling in the evaporator as the compression work and the evaporator inlet quality increase. As a result, an increase in the condenser or gas cooler outlet temperature decreases COP. Increasing the evaporation temperature from 5 °C to 7.5 °C increases the COP as it reduces the compressor work (Fig. 8). R744 required the highest compressor consumption as compatible with COP. It was followed by R1234yf and R134, respectively. An increase in compression increases the compressor discharge temperature (Fig. 9). The lowest and highest compressor discharge temperatures were observed at R1234yf and R744, respectively. The lower compressor discharge temperature will both keep the lubrication quality high and extend the lifetime of the compressor.

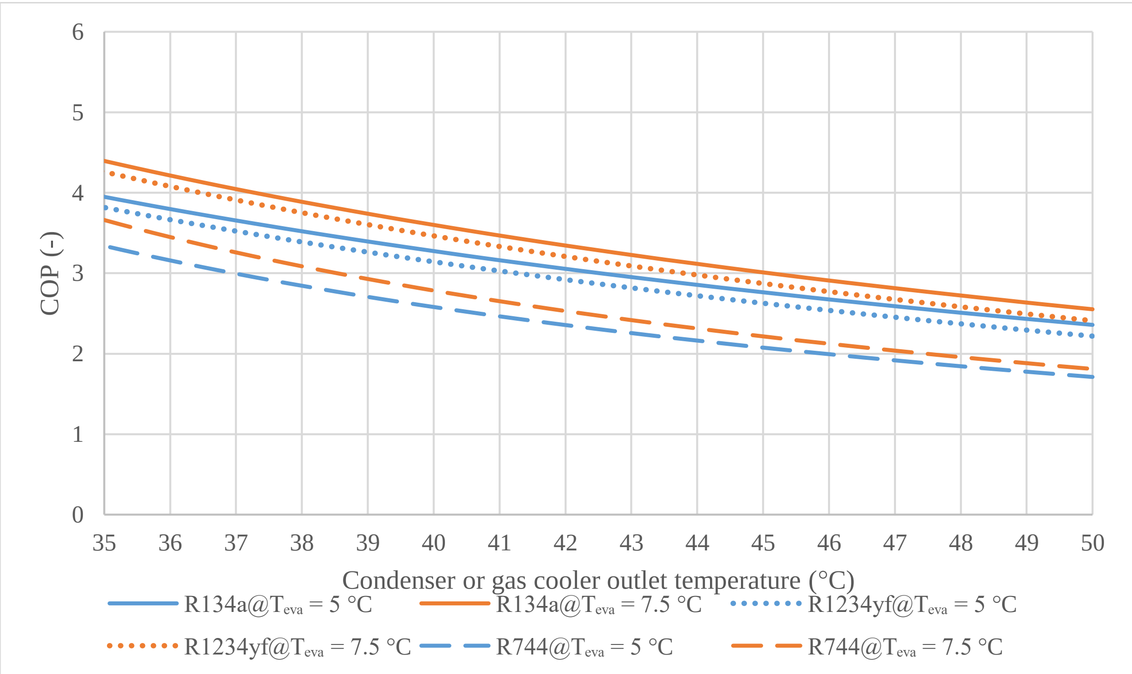

Figure 7. COPs of different refrigerants in the cooling mode.

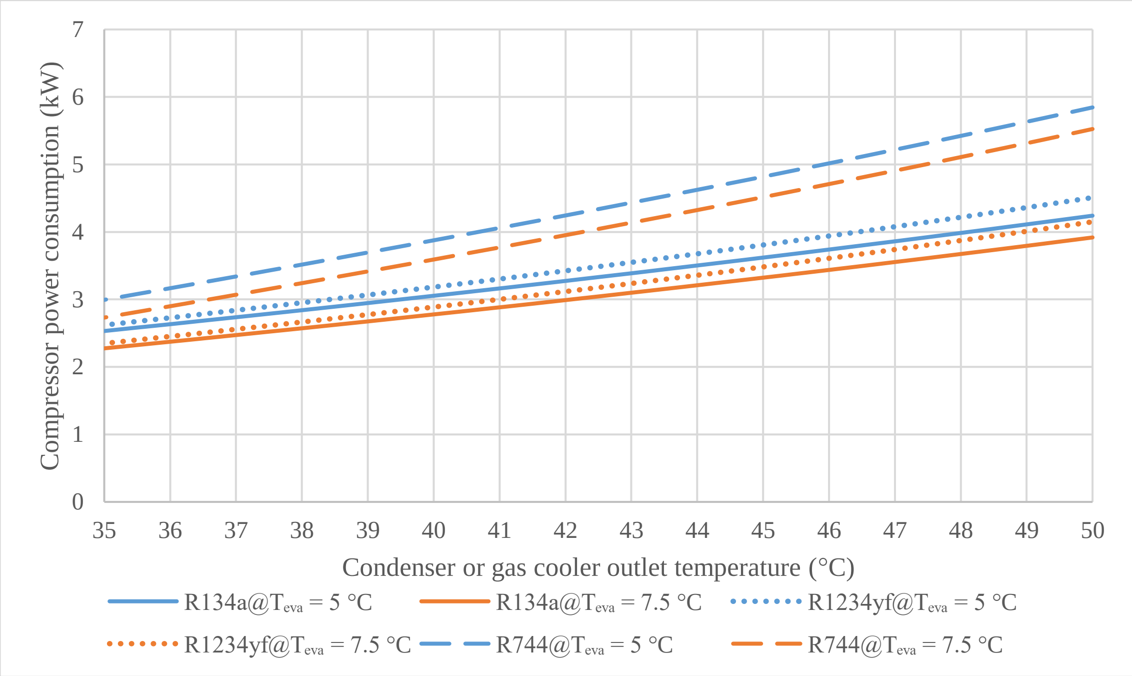

Figure 8. Compressor power consumption of different refrigerants in the cooling mode.

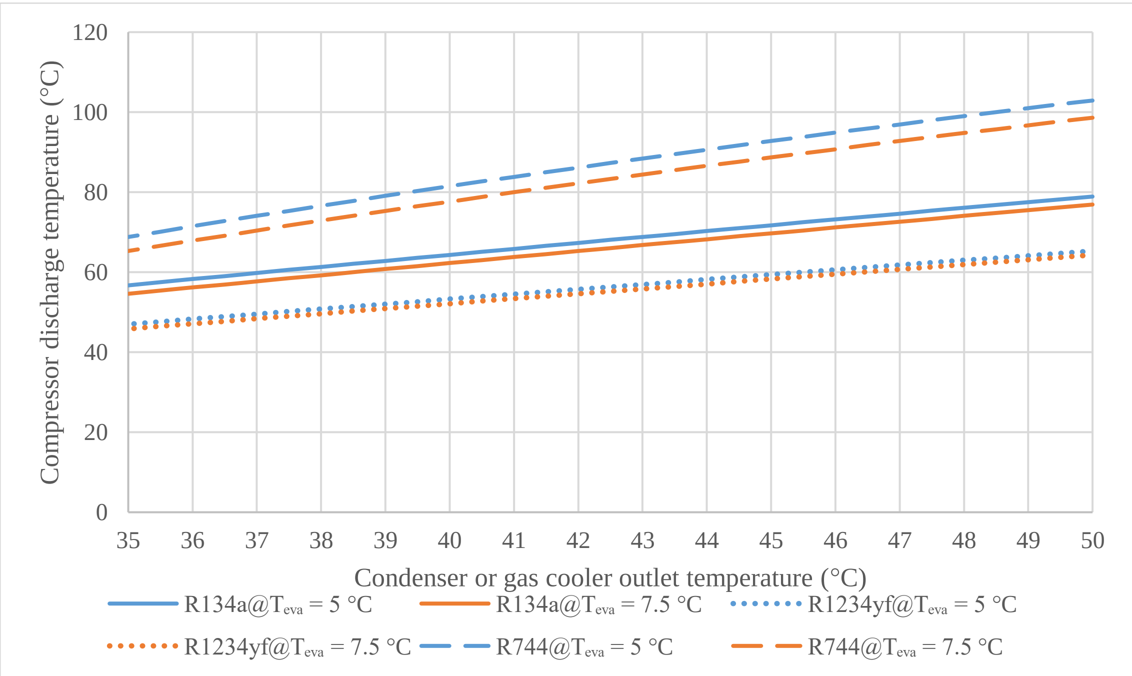

Figure 9. Compressor discharge temperatures of different refrigerants in the cooling mode.

Also in the heating condition, R134a had the highest COP values, followed closely by R1234yf (Fig. 10). R744 gave the lowest COP value for the same operating conditions. As seen from Fig. 11, the COP values increase as the evaporation temperature increases because of requiring less compression work. As the condensation temperature increases, the COP decreases because the compression work increases. Depending on the lowest COP being achieved in R744; the highest compressor consumption was in R744. As with the cooling season results, the lowest and highest compressor discharge temperatures were also obtained for R1234yf and R744, respectively (Fig. 12).

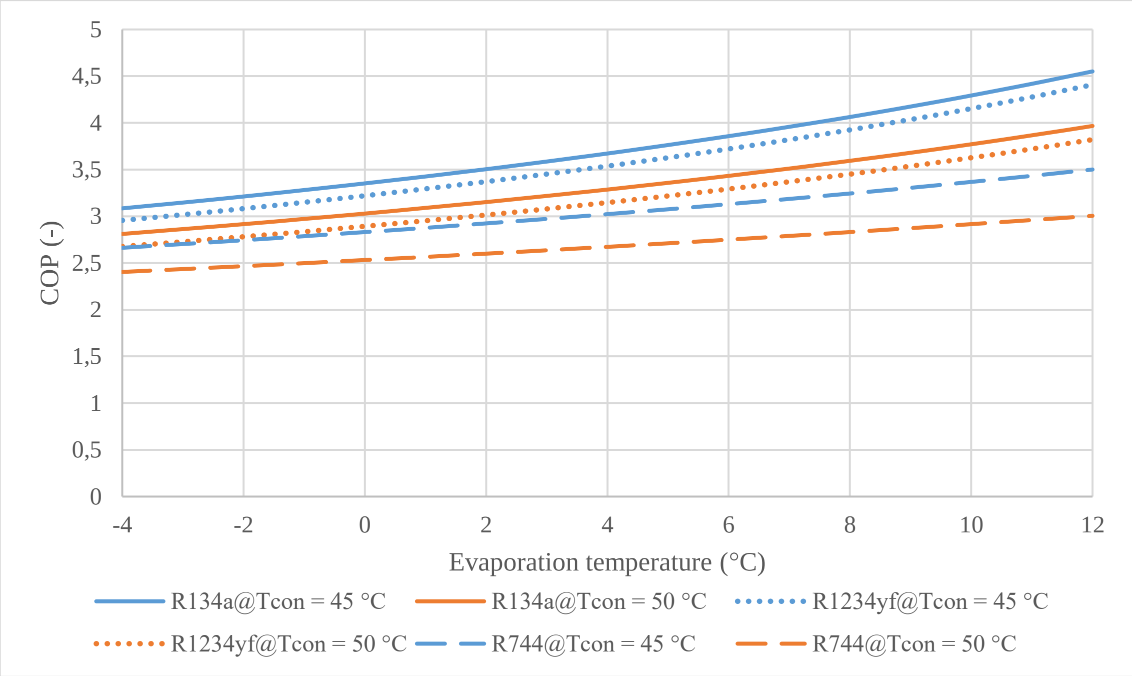

Figure 10. COPs of different refrigerants in the heating mode.

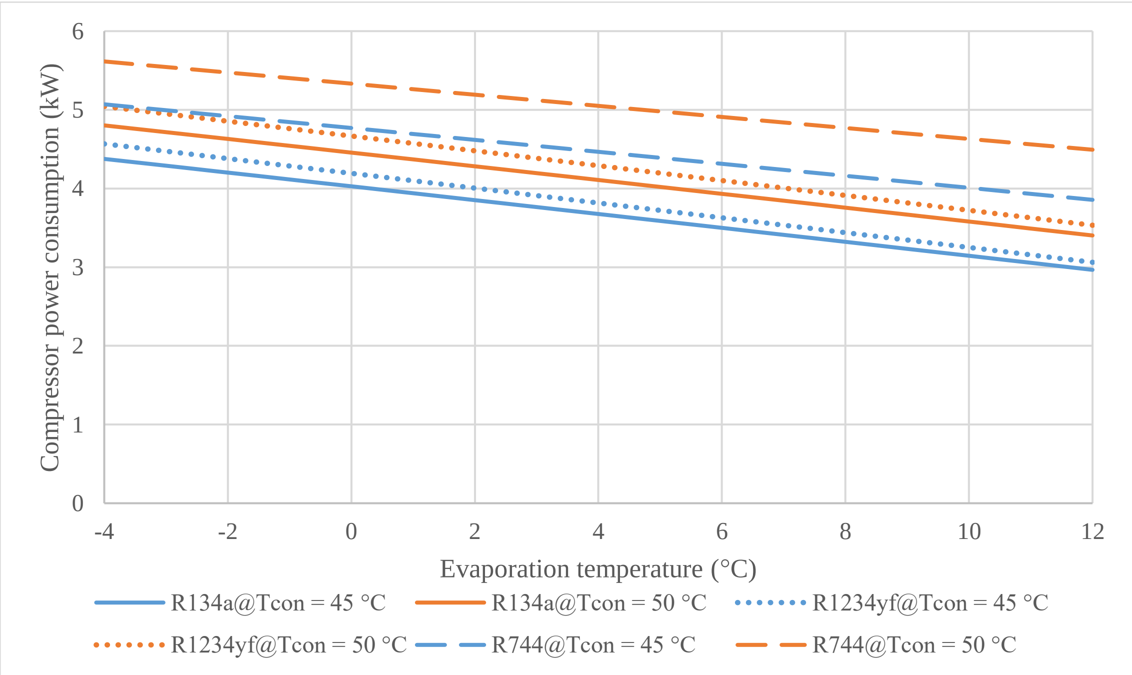

Figure 11. Compressor power consumption of different refrigerants in the heating mode.

4. CONCLUSIONS

Today, where the energy efficiency is important in every field, energy studies are conducted to contribute to the regulations in vehicles. As the electricity consumption of the compressor will be reduced because of the proper selection of the refrigerant, more energy-efficient systems can be designed. In this study, vapor compression cycles with different refrigerants and operating parameters were analyzed. The results were compared in terms of COP, compressor power consumption, and compressor discharge temperature.

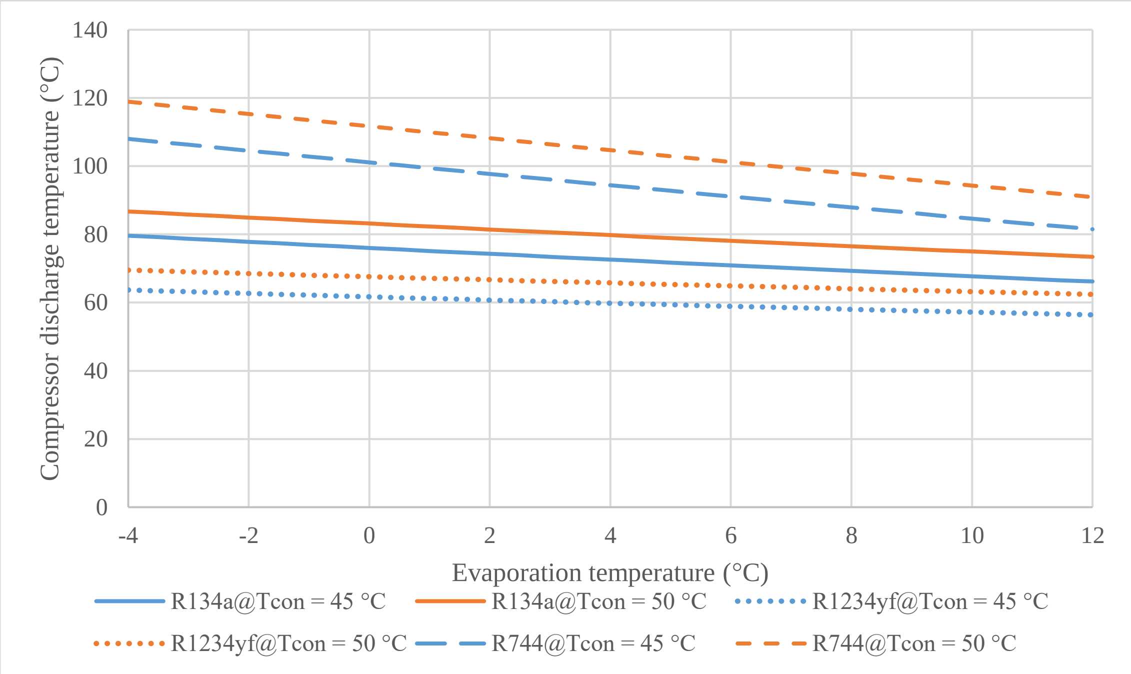

Figure 12. Compressor discharge temperatures of different refrigerants in the heating mode.

The highest COP values were obtained using R134a in both cooling and heating modes and in every operating condition. The closest results to the results obtained using R134a were obtained using the R1234yf refrigerant (on average −4%). When tested under the same operating conditions, R744 gave the lowest COP values (on average −19.3%) in all cases. The highest compressor consumption was obtained in the cycles using R744. It was on average 24.5% higher than the consumption of the R134a system. Compressor discharge temperatures of the R1234yf system were on average 12 °C lower than the R134a system. R744 gave the highest compressor discharge temperatures.

The refrigerant R1234yf has a great similarity with R134a. Thus, it can be used with R1234yf instead of R134a, with minor modifications in mobile heat pump systems. Because R1234yf is much more harmless to the environment compared to R134a. But R744 showed slightly worse results in comparison.

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