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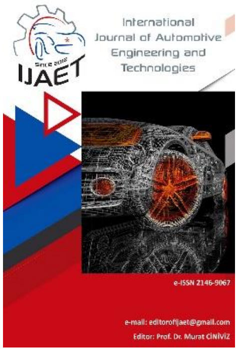

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Thermodynamic performance comparison of a mobile air conditioning system for various HFO and HC alternative refrigerants to replace R134a

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ABSTRACT

The thermodynamic performance of a mobile air conditioning (MAC) system with R134a was compared with the performance offered by some Hydrofluoroolefin (HFO) and Hydrocarbon (HC) refrigerants, namely R1234yf, R1234ze(e), R152a, R290 and R600a. Both the energy and exergy performance merits of the MAC system, including the COP, the rates of exergy destroyed in the components and the exergetic efficiency, were taken into account. In this comparison, the cooling load of the evaporator was varied between 3 kW and 7 kW, both the superheat and subcooling at the outlets of the heat exchangers were assumed to be 5 °C. The refrigerant properties were determined using the REFPROP 9.1 software for a typical evaporating temperature of −2 °C, condenser temperatures of 40 and 50 °C and compressor isentropic efficiency of 55%. Then, the proposed performance parameters of the MAC system were calculated. R1234yf, R1234ze(e) and R290 yielded on average 4.41%, 0.20% and 1.69% lower COP, respectively, whereas R600a and R152a resulted in on average 2.45% and 3.39% higher COP, respectively, relative to R134a. In agreement with the COP findings, R1234yf, R1234ze(e) and R290 provided on average 4.34%, 0.22% and 1.64% lower exergetic efficiency, while R600a and R152a yielded on average 2.38% and 3.35% higher exergetic efficiency, respectively than R134a.

Keywords: Air conditioning, mobile, R1234yf, R1234ze(e), R134a, R152a, R290, R600a

1. Introduction

Mobile air conditioning (MAC) systems were developed in the 1930s [1], and they have been employed in automobiles since then. The first MAC systems used R12, a refrigerant from the Chlorofluorocarbon (CFC) family. However, upon realizing that the chlorine atoms in the CFC refrigerants harmed the stratospheric ozone layer, the use of refrigerants containing chlorine was restricted by the 1987 Montreal Protocol [2]. Consequently, starting in 1994, MAC systems used R134a, a Hydrofluorocarbon (HFC) refrigerant, to replace R12. The ozone-depleting potential (ODP) of R134a is zero but with a global warming potential (GWP) of 1430 [3], it significantly contributes to global warming.

Therefore, in line with the 1997 Kyoto Protocol [4], the European Union put into effect the F-Gas Regulation [5], which mandates that the MAC systems in the new vehicles on the EU market must employ refrigerants with a GWP not exceeding 150. Because R134a could not meet this criterion, R1234yf from the Hydrofluoroolefin (HFO) family was developed as an alternative and employed in the MAC systems of the new vehicles. The operating pressures of R1234yf are close to those of R134a and it has a GWP of only 4 [3]. However, the cooling capacity and coefficient of performance (COP) provided by R1234yf are lower than R134a. Furthermore, it is much more expensive than R134a and it is a refrigerant from the lower-flammability family [3,6]. Although another HFO refrigerant, namely R1234ze(e), was also developed, it was not used in the MAC systems commercially. R1234ze(e) has a GWP of 1, an ODP of zero and is also a refrigerant from the lower-flammability family [7]. In addition to these HFO refrigerants, refrigerants from the Hydrocarbon (HC) family such as R600a (isobutane), R290 (propane) and R152a (difluoroethane) can be used as R134a alternatives. Although all these HC refrigerants have zero ODP, the GWP of both R600a and R290 are 3, while the GWP of R152a is 124. However, R600a and R290 have higher flammability, whereas R152a has lower flammability but not as low as R1234yf and R1234ze(e).

The performance of R1234yf replacing R134a in MAC systems has been studied extensively using theoretical or experimental methods. In these studies, the performance parameters considered were usually obtained from the energy (first law) analysis of the system components.

Many studies showed that R1234yf usually yielded a lower evaporator cooling load and a lower coefficient of performance (COP) [3, 8−11]. As a remedy to this low-performance problem, some studies considered employing an internal heat exchanger (IHX) for transferring heat between the liquid and vapour lines of the MAC system using R1234yf. Thus, the liquid refrigerant passing through the IHX cools down and enters the expansion device at a lower enthalpy. Consequently, the refrigerant entering the evaporator with low enthalpy absorbs more heat from the air stream to be cooled, thereby improving the cooling capacity. Investigators using an IHX in the R1234yf MAC system obtained cooling capacity and COP values close to the values in the R134a system [12−17]. Alkan and İnan [18] observed that the R1234yf MAC system caused higher compressor and expansion device exergy destruction rates but lower evaporator and condenser exergy destruction rates relative to the R134a one. Aral et al. [19] investigated the performance of a MAC/heat pump system using R1234yf and R134a. According to their findings, the cooling load, COP and exergetic efficiency of the R1234yf system were 5.5%, 11.9% and 17.6% lower, respectively than the R134a one in the cooling mode.

A study concluded that the use of R1234yf in a MAC system caused a lower compression ratio, compressor discharge temperature and COP but a higher compressor power relative to R134a [20]. Yataganbaba et al. [21] theoretically investigated the exergy performance of a refrigeration circuit for R134a, R1234yf and R1234ze(e) and determined that both HFO refrigerants are appropriate replacements for R134a. Devecioğlu and Oruç [7] presented a theoretical performance comparison of refrigeration systems using R134a alternatives, namely R1234yf, R1234ze(e), R513a, R445a and R450a. They determined that R450a resulted in comparable COPs with R134a and the best exergetic efficiency was provided by R445a.

The literature survey shows that although the performance of MAC systems with R1234yf was widely investigated, other R134a alternatives were not thoroughly studied. In most of these studies, the performance merits considered were usually the energetic ones and the comparisons were usually based on experimental work. Besides the energy performance, this investigation theoretically evaluates the exergy performance of a MAC system for not only R1234yf but also the other four R134a alternatives, namely R1234ze(e), R152a, R290 and R600a. Then, the results obtained with the alternative refrigerants were compared with those of R134a.

2. Materials and Methods

2.1. The sketch and operation of the MAC system

The sketch of the refrigeration cycle of the MAC system is presented in Figure 1. Its primary elements are the compressor, condenser, expansion device and evaporator.

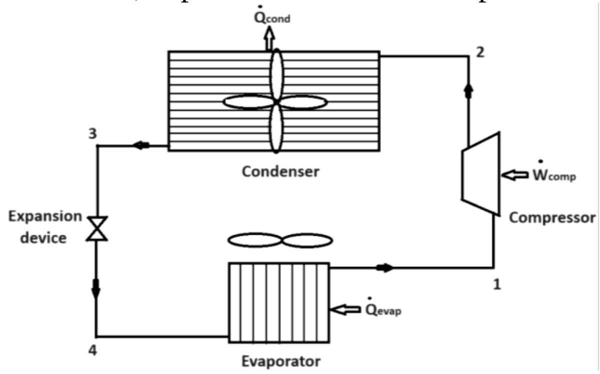

Figure 1. Schematic view of the MAC system

The air stream is pulled from either the ambient (fresh air operation) or passenger compartment (recirculated air operation) and passed over the evaporator by a centrifugal fan. Heat transfers from the air stream to the refrigerant because the refrigerant evaporates at a lower temperature, thus cooling down the air stream. Due to the concurrent condensation of the moisture, a low-temperature air stream with a low moisture content is obtained at the evaporator outlet. This conditioned air stream is sent to the passenger compartment by the centrifugal fan, thus providing thermal comfort inside the compartment. Upon gaining heat from the air stream, the refrigerant evaporates and becomes saturated vapour. Then, it superheats, leaves the evaporator and is drawn into the compressor. Accompanying the pressure rise, the refrigerant temperature rises during the compression. Then, the high-pressure refrigerant leaving the compressor goes into the condenser and transfers heat to the ambient air. As a result, the refrigerant first cools to the condensing temperature and becomes a saturated vapour. Then, it condenses and becomes a saturated liquid, and finally, it subcools below the condensing temperature and exits the condenser. The movement of the ambient air over the condenser is accomplished by an axial fan. Next, the liquid refrigerant enters the expansion device. When the refrigerant is forced to flow through a narrow cross-section in the expansion device, its pressure drops to the evaporating pressure. Accompanying the pressure decrease, the temperature also drops and a low-quality refrigerant with a temperature usually just below 0 °C is obtained at the outlet. Next, the refrigerant leaves the expansion device, passes through the evaporator, and the cycle starts over.

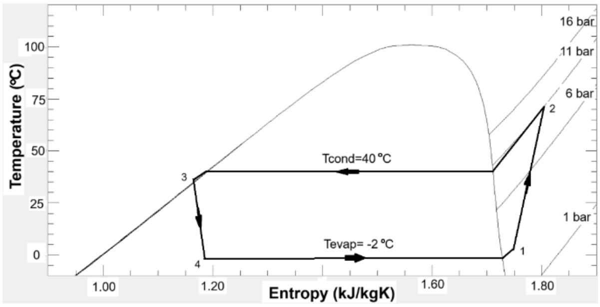

Figure 2. T-s diagram of the refrigeration cycle of the MAC system for R134a

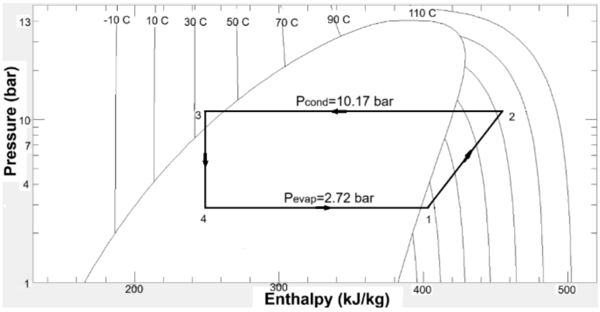

Figure 3. P-h diagram of the refrigeration cycle of the MAC system for R134a

The T-s and P-h diagrams of the refrigeration cycle of the MAC system for the case of using R134a are indicated in Figures 2 and 3, respectively. They were plotted for −2 °C evaporating temperature, 40 °C condensing temperature, 5 °C evaporator superheat, 5 °C condenser subcooling and 55% compressor isentropic efficiency, which were the main input parameters for all refrigerants in this study.

2.2. Energy and exergy analysis of the MAC system

Before analysing the system, the assumptions below are made:

- The operation is in a steady state.
- The kinetic and potential energy variations are negligible.
- The pressure does not change in the evaporator, condenser and refrigerant lines.
- The heat transfer in the refrigerant lines, compressor and expansion device are negligible.

- The dead state of the refrigerants is P_0 = 1.013 bar and $T_0 = T_{cond} - 10$ °C.

By applying the conservation of energy law to its elements, various energetic performance parameters of the MAC system can be determined. If the refrigerant enthalpies entering and exiting the evaporator and the cooling load are known, the refrigerant mass flow rate is

$$\dot{m}_r = \frac{\dot{Q}_{evap}}{h_1 - h_4} \quad (1)$$

The compressor power transferred to the refrigerant is

$$|\dot{W}_{comp}| = \dot{m}_r(h_2 - h_1) \quad (2)$$

The condenser heat rejection rate can be found from

$$|\dot{Q}_{cond}| = \dot{m}_r(h_2 - h_3) \quad (3)$$

Since the expansion device operates adiabatically, the refrigerant enthalpy stays constant in it, i.e.

$$h_4 = h_3 \quad (4)$$

The energy effectiveness of the MAC system can be determined by evaluating its COP from

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

To identify the components leading to thermodynamic inefficiencies along with their magnitudes, an exergy analysis of the MAC system can be performed. For this aim, the following equation [22] can be used.

$$\sum\left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{cv} + \sum \dot{m}_{in}\psi_{in} - \sum \dot{m}_{out}\psi_{out} = \dot{E}x_d \quad (6)$$

where $\dot{E}x_d$ is the exergy destruction rate and ψ is the specific flow exergy defined below.

$$\psi = (h - h_0) - T_0(s - s_0) \quad (7)$$

where subscript *0* represents the dead state.

Because of the heat transfer from the outgoing to the incoming refrigerant streams and friction, exergy is destroyed in the compressor, whose rate can be determined from Equation (6) as

$$\dot{E}x_{d,comp} = \dot{m}_r(\psi_1 - \psi_2) + |\dot{W}_{comp}| \quad (8)$$

As a result of the heat transfer, exergy is destroyed in the condenser, whose rate can be evaluated from [23]

$$\dot{E}x_{d,cond} = \dot{m}_r(\psi_2 - \psi_3) - \left(1 - \frac{T_0}{T_3}\right)|\dot{Q}_{cond}| \quad (9)$$

As a result of the heat transfer, exergy is destroyed in the evaporator, whose rate can be evaluated from [23]

$$\dot{E}x_{d,evap} = \dot{m}_r(\psi_4 - \psi_1) + \left(1 - \frac{T_0}{T_1}\right)\dot{Q}_{evap} \quad (10)$$

Exergy is destroyed in the expansion device due to the sudden expansion of the refrigerant. Assuming that the expansion device operates adiabatically, its rate can be evaluated from

$$\dot{E}x_{d,exp} = \dot{m}_r(\psi_3 - \psi_4) \quad (11)$$

The summation of exergy destructions in its components yields the rate of total exergy destructed in the MAC system, i.e.

$$\dot{E}x_{d,tot} = \dot{E}x_{d,comp} + \dot{E}x_{d,cond} + \dot{E}x_{d,evap} + \dot{E}x_{d,exp} \quad (12)$$

Then, the exergetic efficiency of the MAC system can be evaluated from

$$\eta_{ex} = 1 - \frac{\dot{E}x_{d,tot}}{\dot{E}x_{in}} \quad (13)$$

In this equation, $\dot{E}x_{in}$ is the exergy entering the system, i.e. the compressor power given in Eq. (2).

2.3. Properties of the refrigerants

Important thermodynamic, environmental and safety properties of the considered refrigerants are listed in Table 1. R1234yf and R152a have boiling points close to that of R134a. On the other hand, R600a, R290 and R152a have latent heat of vaporization values considerably higher than R134a, while R1234yf and R1234ze(e) have slightly lower latent heat of vaporization values than R134a. All considered refrigerants have zero ODP values, while all alternative refrigerants except for R152a provide very low GWP values in comparison to R134a. Although R152a has a GWP of 124, it is still below the maximum value allowed by the EU F-Gas Regulation, which is 150.

The most important disadvantage of the considered alternative refrigerants is their flammability. The ASHRAE safety group of R134a is A1, meaning that there is no flame propagation in R134a. The ASHRAE safety group of both R1234yf and R1234ze(e) is A2L, meaning that these refrigerants have lower flammability. The ASHRAE safety group of both R600a and R290 is A3, indicating that these refrigerants are highly flammable. Finally, the safety group of R152a is A2, meaning that it is less flammable than R600a and R290 but has a maximum burning velocity exceeding 10 cm/s. Although A2 and A3 safety group refrigerants can be used in stationary systems, it is risky to employ them in MAC systems, which pose a fire risk during traffic accidents.

2.4. Comparison procedure

The thermodynamic performance of the MAC system operating with the considered refrigerants was evaluated at an evaporating temperature of −2 °C, which is a typical value for most MAC systems. In the evaluation, the evaporator cooling load varied from 3 kW to 7 kW with 1 kW intervals, which are typical loads of MAC systems employed in automobiles. It was assumed that the condenser subcooling and evaporator superheat are both 5 °C. A compressor isentropic efficiency of 55% is accepted as a typical value. Then, the refrigerant properties at various points of the refrigeration circuit were obtained from the REFPROP 9.1 software [26] for the condenser temperatures of 40 and 50 °C. Finally, the performance parameters were determined from Equations (1−13) for all considered refrigerants and operation conditions.

3. Results and Discussion

The performance parameters of the MAC system for R134a and its two HFO and three HC alternatives, namely R1234yf, R1234ze(e), R152a, R290 and R600a, are shown in Figures 4–15 as a function of the evaporator cooling load (cooling capacity) for two condenser temperatures. Moreover, the thermodynamic specifications of the refrigerants at various points are presented in Table 2 for the evaporator cooling load of 5 kW, evaporating temperature of −2 °C and 50 °C condenser temperature as sample results.

The mass flow rate of the refrigerant is exhibited in Figure 4. It tends to increase with the evaporator load and condensing temperature for all refrigerants. As seen in Table 1, R290 has the highest latent heat of vaporization among the considered refrigerants, which is followed by R600a, R152a, R134a, R1234ze(e)and R1234yf in decreasing order. The flow rate is inversely proportional to the latent heat of vaporization of the refrigerant for a fixed evaporator cooling load. As a result, the curves in Figure 4 are in reverse order, i.e. R600a yields the lowest flow rate while R1234yf results in the highest one. Furthermore, to meet the cooling demand, the flow rate gets higher with the rising evaporator cooling load. It also gets higher with the rising condensing temperature for a constant evaporating temperature because of the rising compression ratio, which promotes refrigerant circulation. The average R134a flow rate is 34.47 g/s, while the average R1234yf flow rate is 44.97 g/s, which is 30.44% higher than that of R134a. Furthermore, the average R1234ze(e) flow rate is 37.94 g/s, which is 10.07% higher than that of R134a. R600a yields an average flow rate of 19.00 g/s, which is 44.79% lower than that of R134a. R290 results in an average flow rate of 18.29 g/s, which is 46.93% lower than that of R134a.

Finally, R152a yields an average flow rate of 20.88 g/s, which is 39.40% lower than that of R134a. The R1234yf and R134a mass flow rate results of this investigation agree with Alkan et al. [9], Prabakaran et al. [11], Cho and Park [12] and Aral et al. [19].

Table 1. Thermodynamic, environmental and safety properties of the considered refrigerants [7, 19, 24−26]

Refrigerant	R134a	R1234yf	R1234ze(e)	R152a	R290	R600a
Boiling point at 101.325 kPa (°C)	-26.07	-29.45	-18.97	-24.02	-42.11	-11.75
Critical temperature (°C)	101.06	94.70	109.4	113.30	96.68	134.7
Critical pressure (kPa)	4059	3382	3635	4520	4248	3640
Liquid density at 0°C (kg/m^3)	1294.8	1176.3	1240.1	959.11	528.59	580.58
Vapour density at 0°C (kg/m^3)	14.428	17.647	11.714	8.359	10.351	4.257
Latent heat of vaporization at 0 °C (kJ/kg)	198.60	163.29	184.18	307.11	374.87	354.34
ODP	0	0	0	0	0	0
GWP	1430	4	1	124	3	3
ASHRAE Safety Group	A1	A2L	A2L	A2	A3	A3

Table 2. The thermodynamic specifications of the refrigerants for Q_{evap} = 5 kW, T_{evap} = −2 °C and T_{cond} = 50 °C

Location	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Flow exergy (kJ/kg)
Specifications for R134a ($\dot{m}_r$ = 36.24 g/s)					
1	2.72	3.0	401.86	1.7444	26.55
2	13.18	85.0	463.26	1.8244	62.91
3	13.18	45.0	263.90	1.2134	54.79
4	2.72	-2.0	263.90	1.2358	47.80
Specifications for R1234yf ($\dot{m}_r$ = 47.92 g/s)					
1	2.95	3.0	366.58	1.6143	25.74
2	13.02	69.7	415.78	1.6807	54.16
3	13.02	45.0	262.23	1.2075	48.72
4	2.95	-2.0	262.23	1.2296	41.80
Specifications for R1234ze(e) ($\dot{m}_r$ = 40.01 g/s)					
1	2.01	3.0	387.20	1.6903	17.31
2	9.97	75.4	443.05	1.7649	49.82
3	9.97	45.0	262.25	1.2084	43.20
4	2.01	-2.0	262.25	1.2297	36.53
Specifications for R152a ($\dot{m}_r$ = 21.71 g/s)					
1	2.46	3.0	511.15	2.1475	36.42
2	11.77	102.8	609.35	2.2704	96.16
3	11.76	45.0	280.82	1.2701	80.72
4	2.46	-2.0	280.82	1.2982	71.93
Specifications for R290 ($\dot{m}_r$ = 19.26 g/s)					
1	4.46	3.0	581.27	2.4061	88.80
2	13.69	83.34	699.09	2.5599	158.47
3	13.69	45.0	321.63	1.4029	143.16
4	4.46	-2.0	321.63	1.4488	128.78
Specifications for R600a ($\dot{m}_r$ = 19.95 g/s)					
1	1.46	3.0	559.73	2.3265	19.90
2	6.85	73.4	668.22	2.4725	82.69
3	6.85	45.0	309.09	1.3659	69.93
4	1.46	-2.0	309.09	1.4024	58.49

They all obtained similar tendencies and found that R1234yf yielded a greater flow rate than R134a.

The compressor power is exhibited in Figure 5. It increases with the evaporator load and condensing temperature for all refrigerants. The compressor power depends on the compressor pressure ratio, refrigerant mass flow rate and refrigerant type. As a result of the combined effect of these parameters, R152a absorbs the least compressor power while R1234yf absorbs the greatest power. Because the pressure ratio gets higher with rising condensing temperature, so does the compressor power for all refrigerants. Since the refrigerant flow rate rises with the evaporator cooling load, the compressor power also rises.

The average compressor power for R134a is 1.95 kW. R1234yf, R1234ze(e) and R290 yield on average 4.95%, 0.26% and 1.78% more compressor power, respectively, in comparison to R134a.

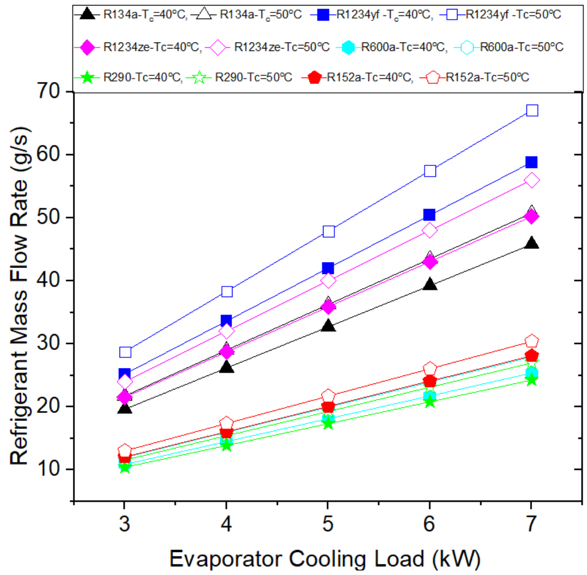

Figure 4. Refrigerant mass flow rate vs. evaporator cooling load

Furthermore, R600a and R152a yield on average 2.48% and 3.50% less compressor power than R134a, respectively. The compressor power results obtained for R1234yf and R134a are in line with Alkan et al. [9] and Aral et al. [19]. They also found that, compared to R134a, R1234yf absorbed more compressor power.

The COP, the ratio of the evaporator cooling load to the compressor power, is presented in Figure 6. The COP stays constant for a specific refrigerant and condensing temperature since the compressor power increases at the same ratio as the cooling load for all refrigerants, no matter what the cooling load is. However, the COP decreases with the rising condensing temperature due to the increasing compressor power. The average COP for R134a is determined as 2.61. R1234yf, R1234ze(e) and R290 yield on average 4.41%, 0.20% and 1.69% lower COP, respectively, whereas R600a and R152a result in on average 2.45% and 3.39% higher COP, respectively, in comparison to R134a. Higher COP values provided by R600a and R152a mean that these two refrigerants are more energy efficient than R134a and other R134a alternatives. The R1234yf and R134a COP findings are in agreement with Devecioğlu et al. [7], Alkan et al. [9], Prabakaran et al. [11], Cho and Park [12], Aral et al. [19] and Mota-Babiloni et al. [24]. They all determined that R1234yf yielded lower COP values than R134a. Furthermore, in agreement with our study, Devecioglu et al. [7] and Mota-Babiloni et al. [24] also obtained that the COP for R1234ze(e) was lower than R134a but higher than R1234ze(e).

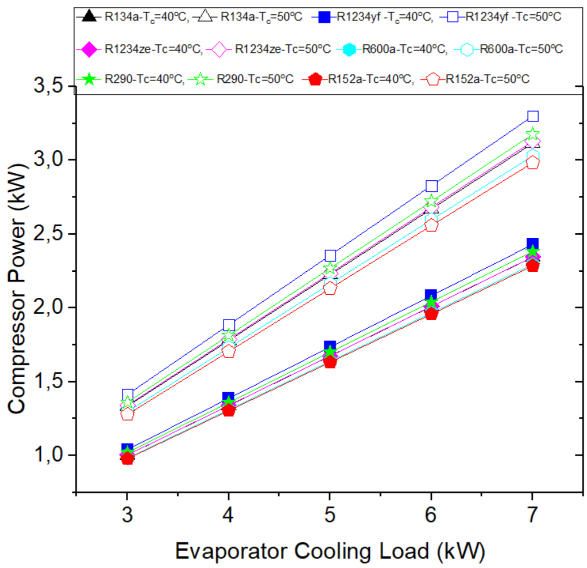

Figure 5. Compressor power vs. evaporator cooling load

The condenser heat rejection rate, the summation of the evaporator cooling load and compressor power, is reported in Figure 7. It increases with the evaporator cooling load and condensing temperature for all refrigerants.

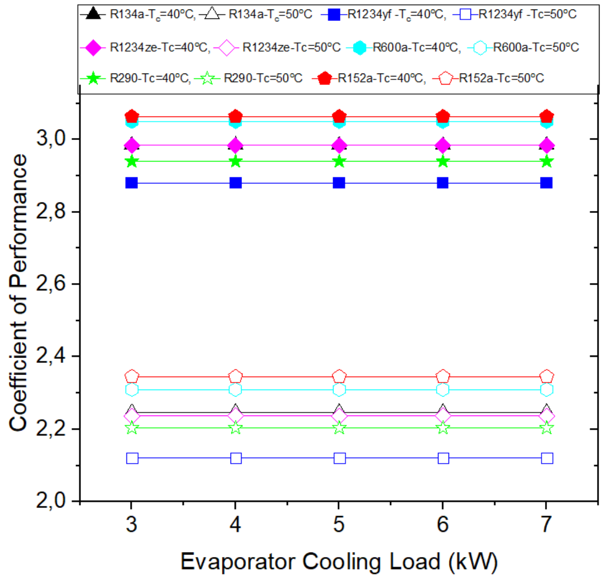

Figure 6. COP vs. evaporator cooling load

Because R1234yf employs the highest compressor power while R152a employs the lowest one, R1234yf rejects the highest heat while R152a rejects the lowest one in the condenser. Because the operation at a high condensing temperature requires more compressor power, the condenser heat rejection rate increases with rising condensing temperature. The average condenser heat rejection rate for R134a is 6.95 kW. R1234yf, R1234ze(e) and R290 yield on average 1.38%, 0.07% and 0.49% more condenser heat rejection rate, respectively, while R600a and R152a reject on average 0.69% and 1.38% less heat in the condenser, respectively, than R134a.

The compressor discharge temperature is indicated in Figure 8. It rises with rising condensing temperature for all refrigerants and the evaporator cooling capacity does not affect it. The refrigerant pressure at the compressor outlet also increases with rising condensing temperature, which in turn increases the compressor discharge temperature. The average compressor discharge temperature for R134a is 78.16°C. R1234yf, R1234ze(e), R600a and R290 yield on average 14.16°C, 8.82°C, 10.52°C and 1.52°C lower compressor discharge temperature, respectively, whereas R152a yields on average 16.36°C higher discharge temperature than R134a. Because high discharge temperatures reduce the lifetime of the compressor oil, they are not welcomed. On the other hand, low discharge temperatures reduce the heat transfer in the

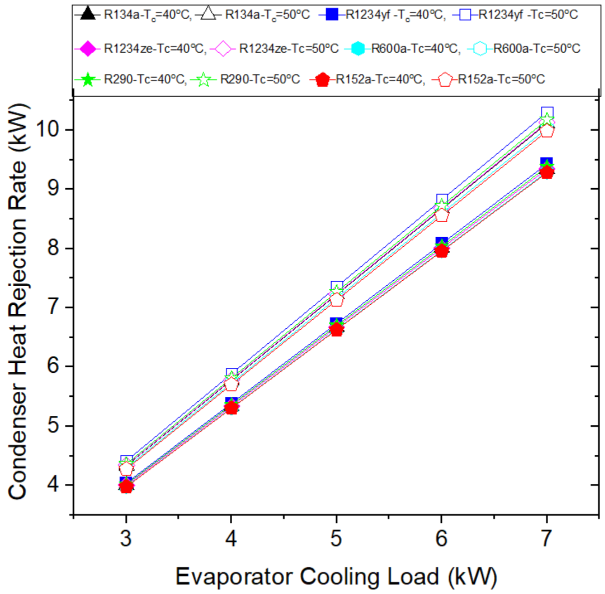

Figure 7. Condenser heat rejection rate vs. evaporator cooling load

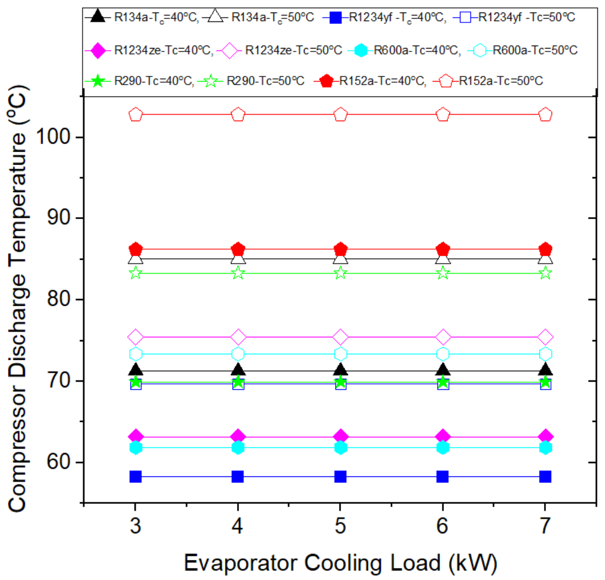

Figure 8. Compressor discharge temperature vs. evaporator cooling load

condenser, thus requiring a larger condenser heat transfer area. The compressor discharge temperature results obtained for R1234yf and R134a are in line with Alkan et al. [9], Prabakaran et al. [11], Cho and Park [12], Aral et al. [19] and Mota-Babiloni et al. [24]. They also found that R1234yf yielded lower compressor discharge temperatures than R134a. Moreover, in line with our investigation, Mota-Babiloni et al. [24] also determined that R1234ze(e) caused discharge temperatures lower than R134a but higher than R1234yf.

The compressor exergy destruction rate is presented in Figure 9. This rate gets higher with the evaporator load and condensing temperature for all refrigerants. The compressor exergy destruction depends on the refrigerant flow rate, compressor pressure ratio and refrigerant type. Because the mass flow rate of R1234yf is higher than other refrigerants, it dominates other factors and causes the greatest destruction rate. Although R152a is not the refrigerant offering the lowest flow rate, the thermodynamic properties and compressor pressure ratio of R152a cause the lowest compressor exergy destruction rates for this refrigerant. The average compressor exergy destruction rate for R134a is 0.796 kW. R1234yf, R1234ze(e), R600a and R290 destroy on average 8.52% 2.64%, 0.50% and 2.01% more exergy in the compressor, respectively, while R152a destroys on average 7.07% less exergy in the compressor in comparison to R134a.

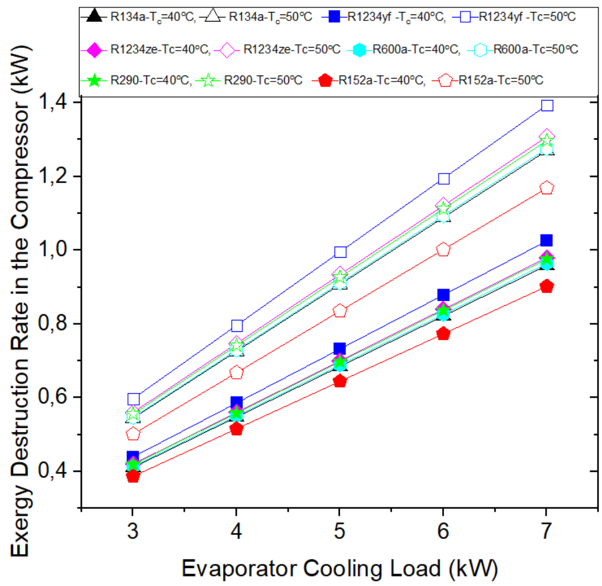

Figure 9. The rate of exergy destroyed in the compressor vs. evaporator cooling load

The condenser exergy destruction rate is shown in Figure 10. It gets higher with the evaporator cooling load and condensing temperature for all refrigerants. The condenser exergy destruction depends on the temperature difference between the fluids passing through and over the condenser, the refrigerant flow rate and the refrigerant type. Because R152a operates with the highest compressor discharge temperatures, it enters the condenser at a high temperature. This causes the highest temperature difference between the fluids and yields the greatest condenser exergy destruction rate. On the other hand, R1234yf and R600a operate with the lowest compressor discharge temperatures, thus causing the lowest condenser exergy destruction rate. The average value of this rate for R134a is determined as 0.168 kW. R1234yf, R1234ze(e), R600a and R290 destroy on average 18.00%,14.60%, 18.85% and 0.27% less exergy in the condenser, respectively, while R152a destroys on average 21.3% more exergy in the condenser in comparison to R134a.

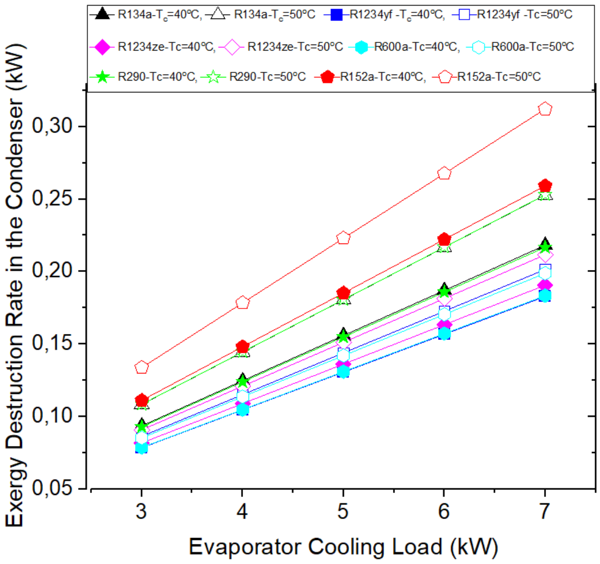

Figure 10. The rate of exergy destroyed in the condenser vs. evaporator cooling load

The evaporator exergy destruction rate is indicated in Figure 11. This rate gets higher with rising evaporator load and condensing temperature for all refrigerants. The evaporator exergy destruction depends on the temperature difference between the fluids passing through and over the evaporator, the refrigerant flow rate and the refrigerant type. Because the evaporating temperatures of all refrigerants are assumed to be −2 °C, the average temperature differences between the fluids are almost identical. Consequently, all refrigerants yield very close evaporator exergy destruction rates. The average value of this rate for R134a is 0.0982 kW. R1234yf, R1234ze(e), R600a and R290 destroy on average 0.50%, 0.79%, 0.19% and 0.08% less exergy in the evaporator, respectively, while R152a destroys on average 0.75% more exergy in the evaporator than R134a.

The expansion device exergy destruction rate is exhibited in Figure 12. This rate increases with the evaporator load and condensing temperature. It depends on the pressure decrease across the expansion device, the refrigerant flow rate, and the refrigerant type. Therefore, the tendency of the expansion device exergy destruction curves is highly similar to the compressor exergy destruction curves. The average exergy destruction rate in this component for R134a is determined as 0.196 kW. R1234yf, R1234ze(e) and R290 yield on average 29.50%, 4.77% and 9.46% more exergy destruction, respectively, whereas R152a and R600a resulted in on average 24.09% and 10.03% less exergy destruction in the expansion device, respectively, than R134a.

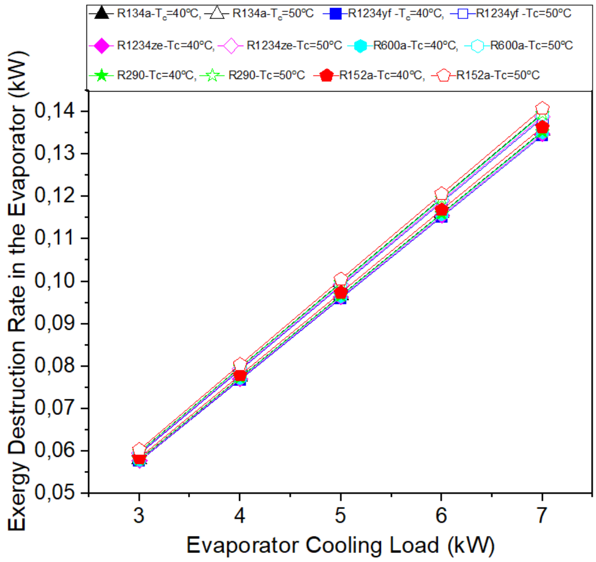

Figure 11. The rate of exergy destroyed in the evaporator vs. evaporator cooling load

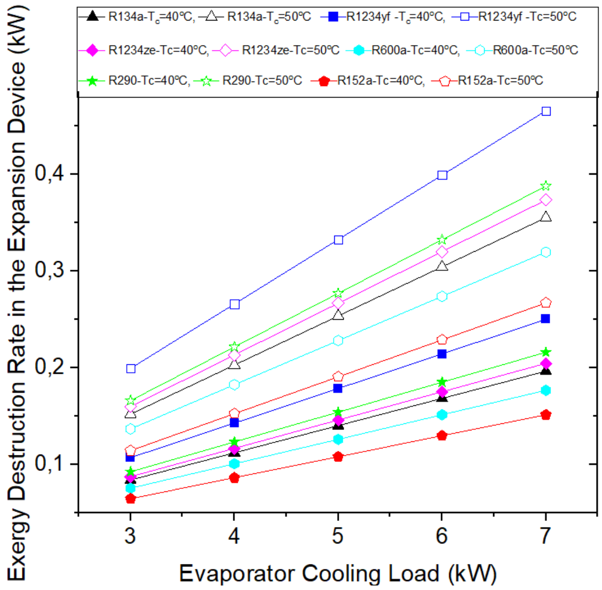

Figure 12. The rate of exergy destroyed in the expansion device vs. evaporator cooling load

The total exergy destruction rate in the MAC system is shown in Figure 13. Similar to the tendencies of its constituents, this rate increases with the evaporator load and condensing temperature. The average total exergy destruction rate for R134a is 1.259 kW. R1234yf destroys on average a total exergy of 1.354 kW, which is 7.54% more than that for R134a. R1234ze(e) destroys on average 1.264 kW total exergy, which is 0.40% more than the exergy destruction of R134a. R600a destroys on average 1.211 kW total exergy, which is 3.77% less than that of R134a. R290 destroys on average 1.293 kW total exergy, which is 2.71% more than R134a. Finally, R152a destroys on average 1.192 kW total exergy, which is 5.33% less than R134a. The results obtained for R1234yf and R134a are in line with Alkan et al. [9] and Yataganbaba et al. [21], who determined that R1234yf caused greater total exergy destruction than R134a. Furthermore, in agreement with our investigation, Yataganbaba et al. [21] reported that the total exergy destroyed by R1234ze(e) is smaller than R1234yf but greater than R134a.

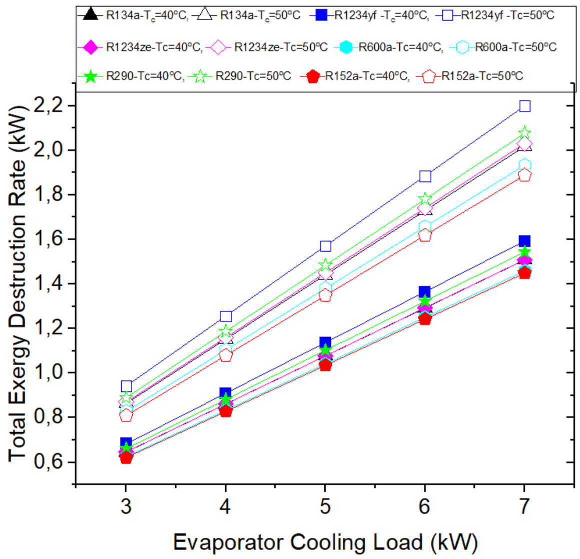

Figure 13. The rate of total exergy destroyed in the MAC system vs. evaporator cooling load

The exergetic efficiency of the MAC system is indicated in Figure 14. The tendencies of the exergetic efficiency curves are similar to the COP curves. In agreement with the higher COP values provided by R152a and R600a, they yield higher exergetic efficiencies than R134a and other alternatives. The average exergetic efficiency for R134a is determined as 35.44%. R1234yf, R1234ze(e) and R290 yield on average 4.34%, 0.22% and 1.64% lower exergetic efficiency, respectively, than R134a. On the other hand, R600a and R152a result in on average 2.38% and 3.35% higher exergetic efficiency, respectively, than R134a. Similar to these findings, Cho and Park [12] determined that R1234yf yielded a lower second-law efficiency than R134a. Furthermore, Yataganbaba et al. [21] reported that R1234yf yielded a lower exergetic efficiency than R134a and that R1234ze(e) provided an exergetic efficiency lower than R134a but higher than R1234yf.

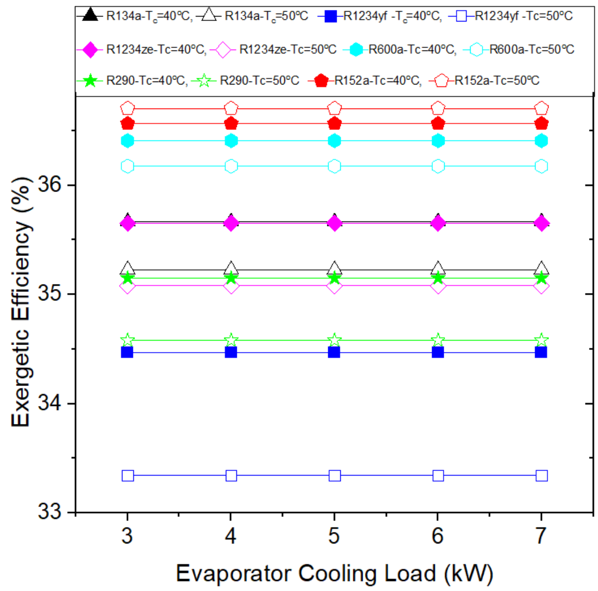

Figure 14. Exergetic efficiency of the MAC system vs. evaporator cooling load

Figure 15 indicates the percent distribution of the destructed exergy in the elements of the MAC system for 5 kW evaporator cooling capacity, −2 °C evaporating temperature and 50 °C condenser temperature.

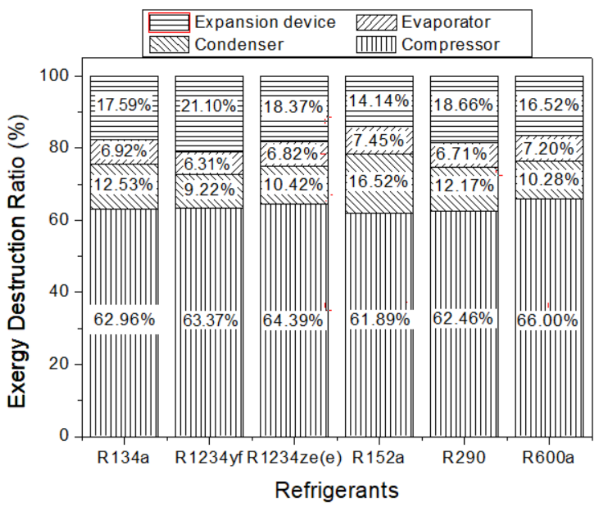

Figure 15. The percent distribution of the destructed exergy in the elements of the MAC system for Q_{evap} = 5 kW, T_{evap} = −2 °C and T_{cond} = 50 °C

The greatest exergy destruction occurred in the compressor while the smallest exergy destruction occurred in the evaporator for all refrigerants. For R152a, the condenser destroys more exergy than the expansion device while the expansion device destroys more exergy than the condenser for the other five refrigerants. Because R1234yf, R1234ze(e), R290 and R600a cause less condenser exergy destruction percent than R134a, a smaller condenser will be sufficient for them in comparison to R134a.

Moreover, R152a requires a larger condenser than R134a to decrease the condenser exergy destruction percent. Yataganbaba et al. [21] also reported that the compressor was the component destroying the highest exergy and the evaporator was the component destroying the lowest exergy for a refrigeration cycle using R134a, R1234yf and R1234ze(e).

4. Conclusions

The thermodynamic performance of an R134a MAC system was compared with those of various R134a alternatives from HFO and HC family, namely R1234yf, R1234ze(e), R152a, R290 and R600a. The comparison was made for typical values of −2 °C evaporating temperature, 40 °C and 50 °C condensing temperatures, 5 °C evaporator superheat, 5 °C condenser subcooling and 55% compressor isentropic efficiency. Then, the performance parameters were evaluated from the conservation of energy and exergy rate balance equations for the typical evaporator cooling loads of 3, 4, 5, 6 and 7 kW. The main conclusions are extracted below.

- The average mass flow rates of R1234yf and R1234ze(e) are 30.45% and 10.07% higher than those of R134a, respectively. On the other hand, R600a, R290 and R152a yield on average 44.79%, 46.93% and 39.40% lower mass flow rates than R134a, respectively.
- R1234yf, R1234ze(e) and R290 yield on average 4.95%, 0.26% and 1.78% more compressor power, respectively, while R600a and R152a result in on average 2.48% and 3.50% less compressor power, respectively, than R134a.
- R1234yf, R1234ze(e) and R290 yield on average 4.41%, 0.20% and 1.69% lower COP, respectively, whereas R600a and R152a result in on average 2.45% and 3.39% higher COP, respectively, compared to R134a.
- R1234yf, R1234ze(e), R600a and R290 yield on average 14.16°C, 8.82°C, 10.52°C and 1.52°C lower compressor discharge temperature, respectively, whereas R152a yield on average 16.36°C higher compressor discharge temperature than R134a.
- R1234yf, R1234ze(e) and R290 destruct on average 7.54%, 0.40% and 2.71% more total exergy, while R600a and R152a destruct 3.77% and 5.33% less total exergy in the MAC system, respectively, relative to R134a.
- R1234yf, R1234ze(e) and R290 yield on average 4.34%, 0.22% and 1.64% lower exergetic efficiency, whereas R600a and R152a result in on average 2.38% and 3.35% higher exergetic efficiency, respectively, in comparison to R134a.
- The compressor causes the greatest exergy destruction, while the evaporator causes the smallest destruction for all refrigerants.
- R1234yf, R1234ze(e), R290 and R600a cause less condenser exergy destruction while R152a cause more condenser exergy destruction than R134a. Therefore, R152a requires a larger condenser while other refrigerants require a smaller condenser in comparison to R134a.

These findings reveal that the performance of R600a and especially R152a surpasses the performance of R134a, R1234yf and R1234ze(e), while R290 shows poorer performance than R134a, and even poorer than R1234yf. Considering that R152a has a GWP of 124, lower than the EU limit value of 150, and is classified in the ASHRAE Safety Group of A2 (lower flammability), it can be employed as an alternative refrigerant in future MAC systems. However, its performance should also be investigated experimentally before using it in MAC systems.

CRedit authorship contribution statement

Eren Kabak: Investigation, Formal analysis, Writing.

Murat Hoşöz: Conceptualization, Methodology, Supervision, Writing, Review&Editing.

Declaration of Competing Interest

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.

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