IMPROVING AUTOMOTIVE AIR CONDITIONING SYSTEMS' (AACS) THERMODYNAMIC PERFORMANCE WITH ECO-FRIENDLY AZEOTROPIC REFRIGERANT BLENDS

H.F. Elattar [1,*], A. Fouda [1], Ahmed Al-Zahrani [1], Rayed S. Alshareef [2], Bandar Awadh Almohammadi [3]

[1] Department of Mechanical and Materials Engineering, Faculty of Engineering, University of Jeddah, Jeddah, 23890, Saudi Arabia.

[2] Department of Chemical Engineering, College of Engineering at Yanbu, Taibah University, Yanbu Al-Bahr, 41911, Saudi Arabia.

[3] Department of Mechanical Engineering, College of Engineering at Yanbu, Taibah University, Yanbu Al-Bahr, 41911, Saudi Arabia

* Corresponding author email: hfalattar@uj.edu.sa

Automotive air-conditioning systems (AACs) traditionally use high-GWP refrigerants, raising environmental concerns. To address this, new azeotropic refrigerant blends—R513A, R513B, R515A, R515B, and R516A—have been developed. These blends offer environmentally friendly alternatives with promising thermodynamic performance. R513A and R513B are suitable replacements for R1234yf and R134a with minimal system modifications, while R516A provides the highest cooling capacity (16.54 kW) and maximum optimal COP (39.84), making it highly effective. R515A ensures low GWP and compressor temperatures, whereas R513A and R513B optimize energy efficiency and safety. Notably, R513A and R513B exhibit the lowest compression ratio (γ) and highest COP values (5.79, 7.23, and 9.40) across various evaporator temperatures, making them ideal for energy-saving applications. Overall, azeotropic refrigerants outperform R1234yf in COP, cooling capacity, and safety, while offering environmentally sustainable solutions for AACs.

Keywords: *GWP; AACs; Environmentally friendly; Azeotropic refrigerants.*

1. Introduction

The development of refrigeration systems dates back to the 19th century, initially relying on hazardous ethers such as dimethyl ether (E170) and ethyl ether (R610) as refrigerants. However, due to safety concerns, efforts were made to find safer alternatives, leading to the adoption of first-generation refrigerants like ammonia (R717), carbon dioxide (R744), and air (R729). These refrigerants remained in use until the 1930s when synthetic refrigerants, known as chlorofluorocarbons (CFCs), became widespread due to their stability, efficiency, and non-toxicity. However, the discovery of CFCs' detrimental impact on the ozone layer, where they catalyze the breakdown of ozone (O_3) into oxygen (O_2), led to regulatory actions aimed at controlling and eventually phasing out these substances. International climate negotiations under the United Nations (UN) played a crucial role in shaping refrigerant policies, beginning with the United Nations Environment Program (UNEP) addressing ozone depletion concerns in 1976. This culminated in the Montreal Protocol of 1987, which mandated the gradual elimination of high-ozone-depletion-potential (ODP) refrigerants [1].

Following the restrictions on CFCs, hydrochlorofluorocarbons (HCFCs) were introduced as transitional refrigerants due to their lower ODP values. However, despite their reduced impact on the ozone layer, HCFCs still posed environmental risks and were subsequently regulated under the Montreal Protocol. This led to the widespread adoption of hydrofluorocarbons (HFCs), which had zero ODP but a significant global warming potential (GWP). As a result, the Kyoto Protocol (1997) targeted HFCs, recognizing their contribution to greenhouse gas emissions and imposing strict regulations on their use [2]. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) further highlighted the high GWP of commonly used refrigerants such as R134a, driving research into environmentally friendly substitutes. Under the 2016 Kigali Amendment to the Montreal Protocol, strict bans on high-GWP refrigerants were implemented. From January 2025, commercial refrigerators and freezers using HFCs with a GWP of 2500 or higher will be prohibited, with further restrictions extending to those with a GWP of 150 or above by January 2029 [3]. Similarly, portable room air conditioners and single-split air conditioners with GWP values exceeding 150 and 750, respectively, will also be banned starting in 2025. The Kigali Amendment represents a major shift in refrigerant policies, aiming to reduce both ozone depletion and the GWP effect by limiting the quantity of refrigerant used in refrigeration, air conditioning, and heat pump equipment based on their CO_2 equivalent emissions. These regulatory changes necessitate the periodic leak testing of equipment, further reinforcing the need for alternative refrigerants with a lower environmental impact. Given these constraints, studies have increasingly focused on evaluating substitute refrigerants in terms of energy efficiency, cooling capacity, and overall environmental performance. Researchers have reported that alternative refrigerants, particularly azeotropic blends, show promise in improving the coefficient of performance (COP) while minimizing environmental impact [4–11]. Prior research on the energy and exergy analysis of azeotropic refrigerants in household and automotive air conditioning (AAC) systems has highlighted their potential to enhance system efficiency and sustainability [12–15].

Azeotropic blends offer distinct advantages over conventional refrigerants, including stability, efficiency, and compatibility with existing systems. These characteristics enhance cooling performance while reducing environmental impact, making them attractive candidates for future refrigerant solutions. Studies have shown that these blends can lead to significant energy savings and improved exergy efficiency, although challenges remain in ensuring long-term system compatibility and operational stability. Mota-Babiloni et al. [16] experimentally investigated the performance of R134a and the low-GWP blend R513A (a combination of R134a and R1234yf) under varying condensing and evaporating conditions. Direk et al. [17] explored the potential of replacing R134a with low-GWP alternatives such as R152a and R444A in AAC systems, assessing performance metrics such as total exergy destruction, compressor power consumption, COP, and cooling capacity. Similarly, Maalem et al. [18] developed simulation software to analyze three new azeotropic blends—R600a+R1234ze+R13I1, R134a+R1234yf+R600a, and R134a+RE170+R600a against conventional R134a in different vapor compression refrigeration configurations. Their results indicated that the R134a+RE170+R600a mixture demonstrated superior COP, environmental sustainability, and cooling performance. Furthermore, Alhendal et al. [19] conducted both experimental and theoretical studies on the energy and exergy performance of low-GWP refrigerants in vehicle air-conditioning systems, demonstrating that refrigerants with a GWP100 value of less than 150 effectively reduced emissions. Ustaoglu [20] performed an advanced exergy analysis of absorption-compression refrigeration cycles, identifying key areas for efficiency improvements and pinpointing component dependencies. A broader search for R134a substitutes has been driven by increasing environmental concerns and stringent regulations aimed at mitigating greenhouse gas emissions [21–39].

The development of refrigeration technology has led to environmental and safety issues, with early refrigerants like ammonia and carbon dioxide being replaced by synthetic refrigerants such as chlorofluorocarbons (CFCs) in the 20th century. However, CFCs were shown to harm the ozone layer, leading to international treaties like the Montreal Protocol and the Kyoto Protocol. High-GWP refrigerants, including hydrochlorofluorocarbons and hydrofluorocarbons, have also caused problems due to their high global warming potential. In industries like automotive air conditioning (AAC), regulatory changes have led to the emergence of low-GWP, non-flammable azeotropic blends, such as R513A, R513B, R515A, R515B, and R516A, aimed at providing equivalent or better thermodynamic performance while adhering to environmental laws. However, thorough studies on these refrigerants, particularly regarding exergy efficiency and component-level irreversibility, remain scarce. This study aims to address this gap by assessing the energy and exergy performance of selected azeotropic refrigerants under reasonable AAC operating conditions. Recent developments in refrigerant chemistry have produced new azeotropic mixtures such as R513A, R513B, R515A, R515B, and R516A that combine environmental friendliness with good thermophysical and safety characteristics. Although these mixtures are promising, comprehensive research evaluating the overall thermodynamic behavior of these blends, especially their exergy performance and component-level irreversibility under realistic automotive air-conditioning (AAC) conditions, remains insufficient. This gap in the literature, along with the urgent need to replace traditional refrigerants, e.g., R134a and R744, with alternatives that meet both regulatory standards and high-performance expectations, drives the current study. This work evaluates key performance criteria, including evaporator capacity, compressor discharge temperature, COP, compressor power, pressure ratio, and exergy efficiency for the selected azeotropic refrigerants using Aspen HYSYS modeling tools. The aim of this research is to assist in creating next-generation AAC systems that are both energy-efficient and environmentally friendly through optimal operating conditions and the measurement of exergy destruction sources within system components. The results are intended to provide practical guidance for engineers and lawmakers seeking low-GWP refrigerant solutions.

2. Refrigerant blends' environmental and physical properties

Azeotropic refrigerants (R513A, R513B, R515A, R515B, and R516A) provide a balance between environmental sustainability and optimal thermodynamic properties, making them viable low-GWP alternatives to conventional refrigerants. R513A and R513B offer efficient cooling with minimal ecological impact, while the non-flammable R515A and R515B enhance safety in commercial refrigeration. R516A further boosts thermal efficiency and reduces greenhouse gas emissions. Collectively, these refrigerants ensure high performance, safety, and compliance with global environmental standards, thereby minimizing the ecological footprint of air conditioning and refrigeration systems. Reference [43] offers comprehensive details on physical and environmental characteristics, including ozone depletion potential (ODP), global warming potential (GWP), safety group classification, chemical composition by mass percentage, normal boiling point (°C), molecular weight (kg/kmol), critical pressure (MPa), and critical temperature (°C).

3. System description

Automotive air conditioning systems (AACs) require efficient evaluation, particularly with new azeotropic refrigerants. Figure 1 illustrates the AAC cycle, which includes the compressor, evaporator, EXV, and condenser. Key parameters—such as condenser pressure, evaporation temperature, and mass flow rate—can be adjusted for optimization. A subcritical model was developed for refrigerants with critical pressures significantly higher than the condenser pressure, ensuring optimal system performance [44].

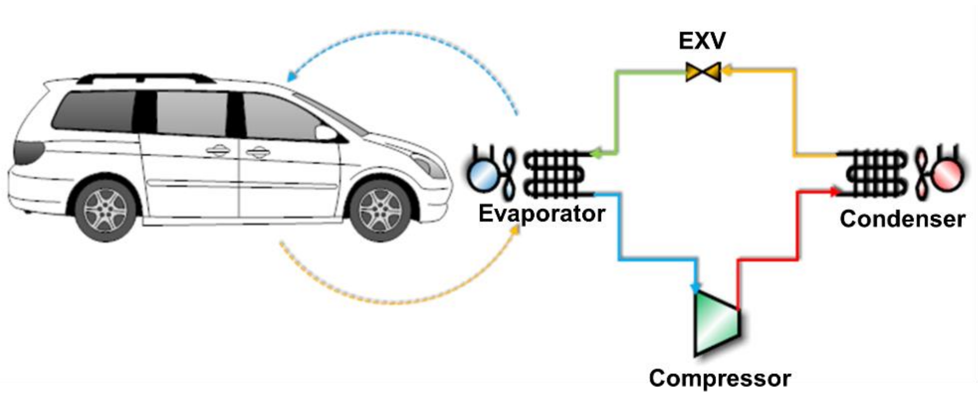

Figure 1. Schematic diagram of AACs.

4. Thermodynamic modeling and assumptions

Azeotropic refrigerants in AACs were evaluated using Aspen HYSYS V12.2® (AspenTech, Bedford, MA, USA) [45], a widely used process simulator in academia and engineering due to its reliability in analyzing complex systems. Its intuitive interface facilitates both conceptual and operational planning. With extensive pre-built models and property packages, Aspen HYSYS integrates material and energy flows for simulating both static and dynamic processes involving chemical and hydrocarbon fluids. The AAC simulation model encompasses compressors, expansion valves, condensers, evaporators, and related components.

4.1. System assumptions

To simplify and ensure accuracy in modeling azeotropic refrigerant replacements in AACs, steady-state conditions were assumed, with negligible effects from kinetic energy and gravity. The baseline ambient temperature and pressure were set at 25°C and 101.325 kPa, respectively, and heat or pressure losses during transfer were neglected. The refrigerant was considered saturated at the evaporator outlet. These assumptions, summarized in Table 2, support a consistent analysis framework. The operational parameters (Table 2) were selected to represent realistic AAC scenarios: evaporator temperatures (5–15°C) align with SAE J2765 standards for passenger comfort [46]. Condenser pressures (5–15 MPa) cover subcritical operation while avoiding near-critical extremes for most blends. Mass flow rates (0.05–0.15 kg/s) were derived from typical system capacities (3–5 kW) and refrigerant properties. Optimal pressures (P_{opt}) were determined through parametric sweeps to maximize COP under baseline conditions (t_3 = 35°C, t_{evap} = 7.5°C).

4.2. Thermodynamic model analysis

The study examines COP, pressure ratio, exergy efficiency, compressor discharge temperature, evaporator capacity, and compressor power by analyzing energy and exergy in AACs using various azeotropic refrigerant blends. Energy analysis applies the first law of thermodynamics under steady-state conditions, assuming minimal changes in kinetic and potential energy. Unlike energy, exergy is dissipated in both efficient and inefficient processes. Thermal exergy analysis helps identify thermodynamic inefficiencies, achieved through steady-state exergy balance equations for AAC components. Detailed formulations of the energy and exergy balance equations are provided in References [13], [15], and [39].

Table 2. Operating parameters' values and ranges.

Parameter	Value / Range
Condenser pressure, P_2	5 – 15 MPa
Evaporator temperature (average), t_{evap}	5 – 15 ºC
Condenser outlet temperature, t_3	20 – 40 ºC
Refrigerant flow rate, $\dot{m}_r$	0.05 – 0.15 kg/s
Compressor isentropic efficiency, η_{is}	80%
Saturated vapor refrigerant at evaporator outlet, x_1	1
Pressure drops in condenser and evaporator, $\Delta P_{evap} = \Delta P_{cond}$	0
Optimal condenser pressure, P_{opt} *(at t_3 = 35 ºC, t_{evap} = 7.5 ºC, $m^{\bullet}_r$ = 0.075 kg/s)*	
$P_{opt,\ R1234yf}$ & $P_{opt,\ R516A}$	0.9 MPa
$P_{opt,\ R513A}$ & $P_{opt,\ R513B}$	0.92 MPa
$P_{opt,\ R515A}$ & $P_{opt,\ R515B}$	0.70 MPa

4.3. Model validation

Model validation ensures the accuracy of the AAC simulation in Aspen HYSYS. R-134a and R-1234yf were selected, as they are key components in the studied azeotropic blends. This confirms Aspen HYSYS's capability to simulate diverse refrigerant compositions. Currently, there are no experimental data to validate AAC simulations for these blends. The subcritical cycles of R-134a and R-1234yf were validated using Mota-Babiloni et al.'s parameters [47], which included a condensing temperature of 35ºC, superheating and subcooling of 10.5ºC and 7ºC, and 65% isentropic efficiency. Table 3 presents a maximum relative error of 8.3%, 14.3%, and 10% for $Q^{\bullet}_{evap}$, $W^{\bullet}_{comp}$, and COP for R-134a, and 5.8%, 16.4%, and 11.5% for R-1234yf, confirming the model's accuracy.

5. Results and Discussions

This study aims to evaluate environmentally safe azeotropic refrigerant mixtures (R513A, R513B, R515A, R515B, and R516A) for automotive air conditioning (AAC) systems, focusing on their thermodynamic performance. Using Aspen HYSYS, the analysis assesses energy and exergy properties, examining key performance metrics such as compressor discharge temperature, evaporator capacity, cycle COP, refrigerant mass flow rate, and condenser outlet temperature. The study evaluates their impact on compressor power, pressure ratio, and exergy efficiency to identify optimal refrigerants for AAC systems.

5.1. Environmental impacts of the studied azeotropic refrigerants

The investigated azeotropic refrigerants—R513A, R513B, R515A, R515B, and R516A—demonstrate potential to reduce greenhouse gas emissions and mitigate climate change. Their low global warming potential (GWP) compared to conventional refrigerants enhances their environmental appeal. R513A and R513B offer comparable or superior performance with reduced environmental impact, while R515A and R515B provide safer, non-flammable options for commercial applications. R516A further supports sustainability with its low GWP and efficient thermodynamic properties. Collectively, these refrigerants align with global environmental regulations, reducing the carbon footprint of cooling systems and advancing sustainable cooling technologies.

Table 3: Model validation with reported results [47].

Operating conditions			**Performance parameters**								
			$\dot{Q}_{evap}$ ***(kW)***			$\dot{W}_{comp}$ ***(kW)***			***COP***		
	T_{evap} (°C)	$\dot{m}_r$ (kg/s)	Exp., [47]	Present model	Error (%)	Exp., [47]	Present model	Error (%)	Exp., [47]	Present model	Error (%)
R-134a	-15	0.004	0.701	0.642	8.3	0.468	0.446	4.8	1.496	1.440	3.7
	-10	0.006	0.984	0.984	0.0	0.466	0.466	0.0	2.114	2.112	0.1
	-5	0.007	1.221	1.172	4.0	0.470	0.474	0.8	2.598	2.474	4.8
	0	0.009	1.546	1.538	0.5	0.475	0.523	10.1	3.255	2.941	9.6
	5	0.011	1.863	1.916	2.8	0.470	0.537	14.3	3.964	3.566	10.0
	10	0.013	2.264	2.218	2.0	0.460	0.499	8.5	4.922	4.444	9.7
	12.5	0.014	2.496	2.507	0.5	0.452	0.498	10.3	5.521	5.029	8.9
Operating conditions			$\dot{Q}_{evap}$ (kW)			$\dot{W}_{comp}$ (kW)			COP		
	T_{evap} (°C)	$\dot{m}_r$ (kg/s)	Exp., [47]	Present model	Error (%)	Exp., [47]	Present model	Error (%)	Exp., [47]	Present model	Error (%)
R-1234yf	-15	0.004	0.836	0.851	1.9	0.468	0.469	0.15	1.784	1.815	1.7
	-10	0.006	1.029	1.089	5.8	0.474	0.517	9.0	2.171	2.107	2.9
	-5	0.007	1.307	1.337	2.3	0.476	0.540	13.5	2.745	2.475	9.8
	0	0.009	1.546	1.519	1.7	0.485	0.515	6.2	3.189	2.951	7.4
	5	0.011	1.960	2.018	2.9	0.483	0.562	16.4	4.059	3.591	11.5
	10	0.013	2.313	2.377	2.8	0.465	0.529	13.8	4.974	4.492	9.7
	12.5	0.014	2.474	2.561	3.5	0.455	0.502	10.3	5.433	5.098	6.2

5.2. Parametric studies

5.2.1 Impact of Condenser Pressure, P

Figure 2 illustrates the effects of condenser pressure (P_2) on evaporator capacity ($\dot{Q}_{evap}$), compressor power ($\dot{W}_{comp}$), pressure ratio (γ), discharge temperature (t_2), coefficient of performance (COP), and exergy efficiency (η_{ex}). As P_2 increases, $\dot{Q}_{evap}$ decreases due to a reduced temperature differential, which limits heat absorption (Fig. 2a). Simultaneously, $\dot{W}_{comp}$, γ, and t_2 rise, as higher pressures require more compressor work (Figs. 2b–d). COP and η_{ex} decline with increasing P_2, driven by lower system efficiency and energy conversion (Figs. 2e–f). These trends are consistent across R513A, R513B, R515A, R515B, and R516A, with R516A exhibiting the highest $\dot{Q}_{evap}$ (10.9 kW) and W•comp (6.9 kW) due to its thermophysical properties. Increasing P_2 from 1 MPa to 15 MPa raises W•comp by approximately 360% and reduces COP from 6.5 to 0.5 (a 92% drop), highlighting the adverse impact of higher condenser pressures on system performance.

5.2.2 Impact of Average Evaporator Temperature, t_{evap}

Figure 3 illustrates the effects of evaporator temperature (t_{evap}) on performance parameters—evaporator capacity ($\dot{Q}_{evap}$), compressor power ($\dot{W}_{comp}$), pressure ratio (γ), discharge temperature (t_2), COP, and exergy efficiency (η_{ex}) for refrigerants R513A, R513B, R515A, R515B, and R516A. Increasing t_{evap} enhances Q•$_{evap}$ due to greater enthalpy differences and improved heat absorption. Higher t_{evap} also reduces

$W^{\bullet}_{comp}$, γ, and t_2, as lower pressure ratios decrease compressor workload and discharge temperatures. COP and η_{ex} improve with rising t_{evap}, driven by increased system efficiency and reduced irreversibility. These trends are consistent across all refrigerants, with R513A and R513B exhibiting the highest COP and lowest $W^{\bullet}_{comp}$, followed by R516A. Specifically, $Q^{\bullet}_{evap}$ for R516A reaches 11.2 kW, increasing by 4.7% as t_{evap} rises from 5°C to 15°C, while COP improves by 59% across all refrigerants.

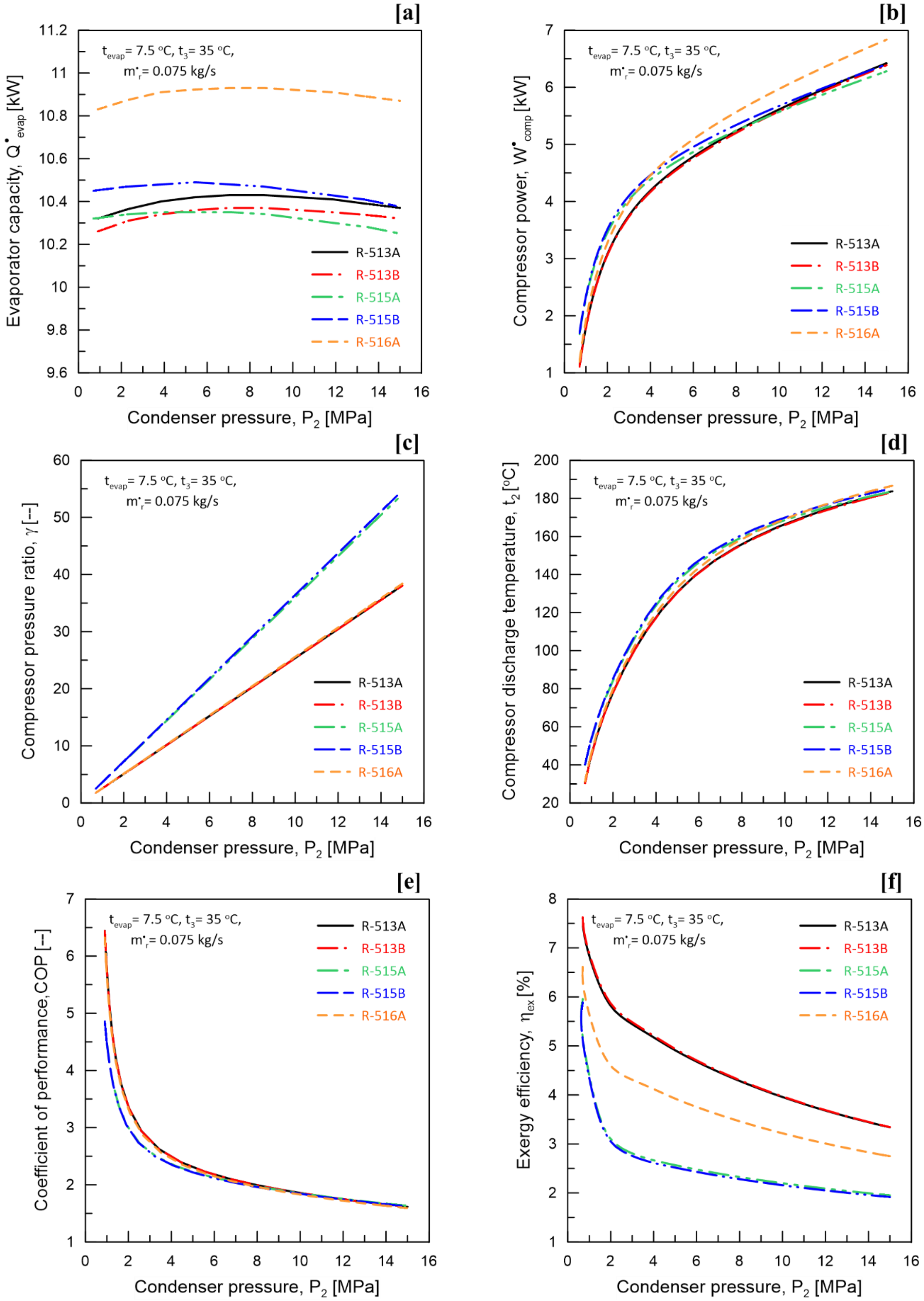

Fig. 2. Influence of condenser pressure on AACs performance.

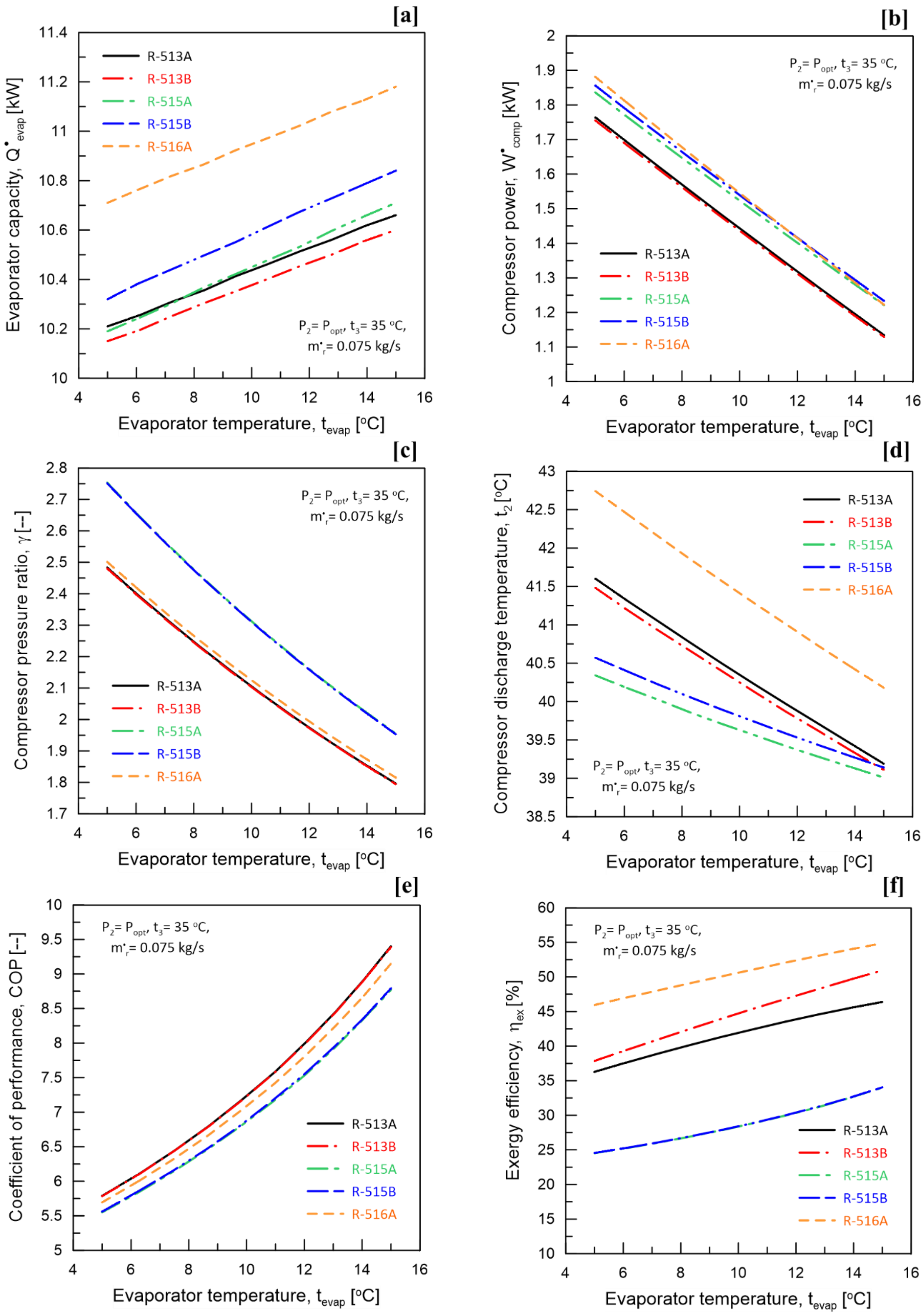

Fig. 3. Influence of evaporator temperature on AACs performance.

5.2.3 *Impact of Condenser Outlet Temperature, t_3*

Figure 4 illustrates the effects of condenser outlet temperature (t_3) on evaporator capacity ($Q^{\bullet}_{evap}$), COP, and exergy efficiency (η_{ex}) for refrigerants R513A, R513B, R515A, R515B, and R516A. Increasing t_3 reduces $Q^{\bullet}_{evap}$ due to a smaller temperature differential, which limits heat absorption. While t_3 has no direct impact on $W^{\bullet}_{comp}$, it raises γ and t_2, as higher condenser pressures increase both the pressure differential and discharge temperatures. COP and η_{ex} decline with rising t_3, driven by reduced evaporator performance and increased irreversibility. These trends are consistent across all refrigerants, with R516A showing the highest $Q^{\bullet}_{evap}$ (12.5 kW), which decreases by 12.5% as t_3 rises from 20°C to 34°C. R513A and R513B exhibit the highest COP (7.48), decreasing by 13%, and the lowest $W^{\bullet}_{comp}$ (1.6 kW), followed by R515A, R515B, and R516A.

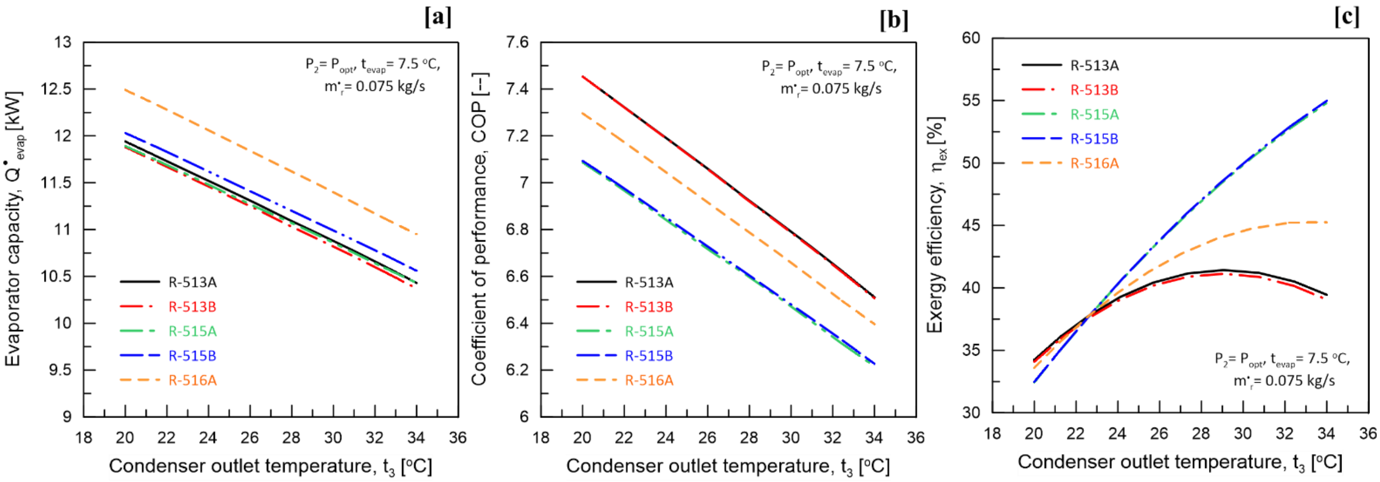

Fig. 4. Influence of condenser outlet temperature on AACs performance.

5.2.4 *Impact of Refrigerant Mass Flow Rate, $m^{\bullet}_r$*

Figure 5 illustrates the effects of refrigerant mass flow rate ($m^{\bullet}_r$) on evaporator capacity ($Q^{\bullet}_{evap}$) and compressor power ($W^{\bullet}_{comp}$) for refrigerants R513A, R513B, R515A, R515B, and R516A. Increasing $m^{\bullet}_r$ enhances $Q^{\bullet}_{evap}$ due to greater heat absorption but also raises $W^{\bullet}_{comp}$ and t_2 as the compressor works harder. The pressure ratio (γ) remains relatively stable, influenced more by temperature and pressure conditions than by flow rate. COP and η_{ex} initially improve with higher $m^{\bullet}_r$ due to increased evaporator capacity, but may decline if compressor power consumption outweighs the benefits. These trends are consistent across all refrigerants, with R516A showing the highest $Q^{\bullet}_{evap}$ (21.5 kW at $m^{\bullet}_r$ = 0.15 kg/s) and R513A/R513B exhibiting the highest COP (6.45). $W^{\bullet}_{comp}$ increases by 200% as $m^{\bullet}_r$ rises from 0.05 kg/s to 0.15 kg/s.

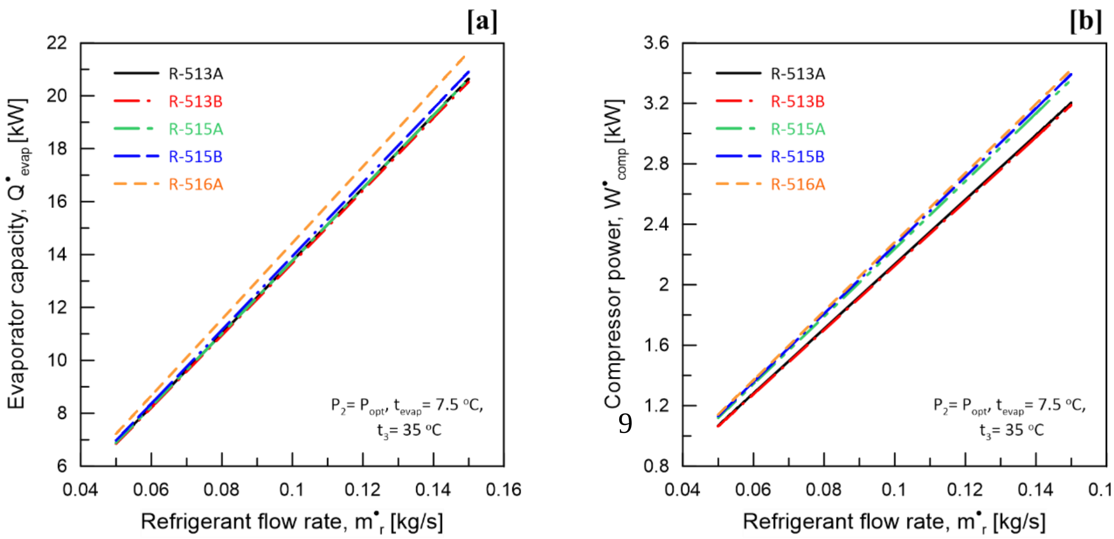

Fig. 5. Influence of refrigerant flow rate on AACs performance.

5.3. Assessments and comparisons of studied refrigerant blends

The environmental and thermophysical properties of refrigerant blends R513A, R513B, R515A, R515B, and R516A were evaluated, focusing on GWP and performance in HVAC systems. A comparative analysis at $P_2 = P_{opt}$, $t_3 = 35°C$, and $m^{\cdot U} = 0.075$ kg/s (Table 4) revealed distinct performance trends across evaporator temperatures (t_{evap} = 5°C, 10°C, 15°C). R516A consistently achieved the highest evaporator capacity ($Q^{\bullet}_{evap}$), peaking at 11.18 kW at t_{evap} = 15°C, but it also exhibited higher compressor power ($W^{\bullet}_{comp}$) and discharge temperatures (t_2), raising durability concerns. R513A demonstrated superior energy efficiency, with the highest COP (9.40 at t_{evap} = 15°C) and lowest pressure ratio (γ), making it ideal for energy-saving applications. R515A, while showing lower t_2, underperformed in COP and γ, highlighting the trade-offs between efficiency, cooling performance, and system reliability.

Table 4: Comparisons of the studied refrigerant blends at P_2= P_{opt}, t_3= 35 °C, and $\dot{m}_r$ = 0.075 kg/s.

Term	t_{evap} (°C)	R-513A	R-513B	R-515A	R-515B	R-516A	R-1234yf
$Q^{\bullet}_{evap}$ *(kW)*	5	10.21	10.15	10.19	10.32	10.71	9.207
$W^{\bullet}_{comp}$ *(kW)*		1.764	1.755	1.836	1.856	1.881	1.622
γ		2.483	2.48	2.753	2.751	2.501	2.444
t_2 *(°C)*		41.6	41.48	40.34	40.57	42.74	39.72
COP		5.79	5.78	5.55	5.56	5.69	5.67
$Q^{\bullet}_{evap}$ *(kW)*	10	10.44	10.38	10.45	10.58	10.95	9.435
$W^{\bullet}_{comp}$ *(kW)*		1.443	1.436	1.523	1.539	1.545	1.329
γ		2.105	2.103	2.312	2.31	2.125	2.080
t_2 *(°C)*		40.35	40.25	39.63	39.81	41.41	38.84
COP		7.23	7.23	6.86	6.87	7.09	7.09
$Q^{\bullet}_{evap}$ *(kW)*	15	10.66	10.6	10.71	10.84	11.18	9.66
$W^{\bullet}_{comp}$ *(kW)*		1.134	1.129	1.221	1.233	1.222	1.047
γ		1.796	1.794	1.955	1.953	1.815	1.781
t_2 *(°C)*		39.19	39.11	39.01	39.14	40.18	38.04
COP		9.4	9.39	8.77	8.79	9.15	9.22

Figure 6 presents further analysis of the component- level exergy destruction across all examined refrigerant blends. The expansion valve (EXV) for R 513 A and R 513 B is the primary cause of exergy destruction, accounting for approximately 49. 2% and 55.3. 3% of the total system exergy losses, respectively. This high destruction rate, attributed to the irreversible throttling process with no beneficial work extraction, emphasizes the necessity for potential alternatives like ejectors or expansion work recovery devices in future designs. The pressure drops occur without useful work recovery, resulting in increased entropy generation. In comparison, R 516 A experiences its greatest exergy loss in the compressor, which constitutes 48. 48.85% of all losses. A higher pressure ratio and discharge temperature suggest greater mechanical and thermal inefficiencies in the compression process for this refrigerant. These losses could be mitigated through optimal compressor design or multi- stage compression with intercooling or advanced compressor designs. Showcasing exceptional thermal performance and low irreversibility during heat absorption, the evaporator displays values around 0. 01% for R 513 A, R 513 B, and R 516 A. Conversely, R 515 A and R 515 B exhibit considerable evaporator- related irreversibility, with exergy destructions of 43. 83% and 44. 05%, respectively. This signifies poor heat exchange qualities and potential temperature profile mismatches, necessitating improved evaporator design or enhanced refrigerant flow control in systems using these combinations. Overall, the study highlights the need for targeted improvements based on the primary causes of inefficiencies for each refrigerant. Key initiatives to enhance the overall exergy efficiency of vehicle air conditioning systems utilizing azeotropic refrigerants include improving compressor efficiency for R 516 A, revamping the expansion process for R 513 A/B, and enhancing evaporator performance for R 515 A and R 515 B. These results underscore the importance of component- level thermodynamic behavior in determining system efficiency and emphasize the necessity for focused design modifications, such as incorporating expander- based expansion devices, optimizing compressor performance, and improving evaporator heat transfer, to reduce exergy destruction and enhance overall system performance.

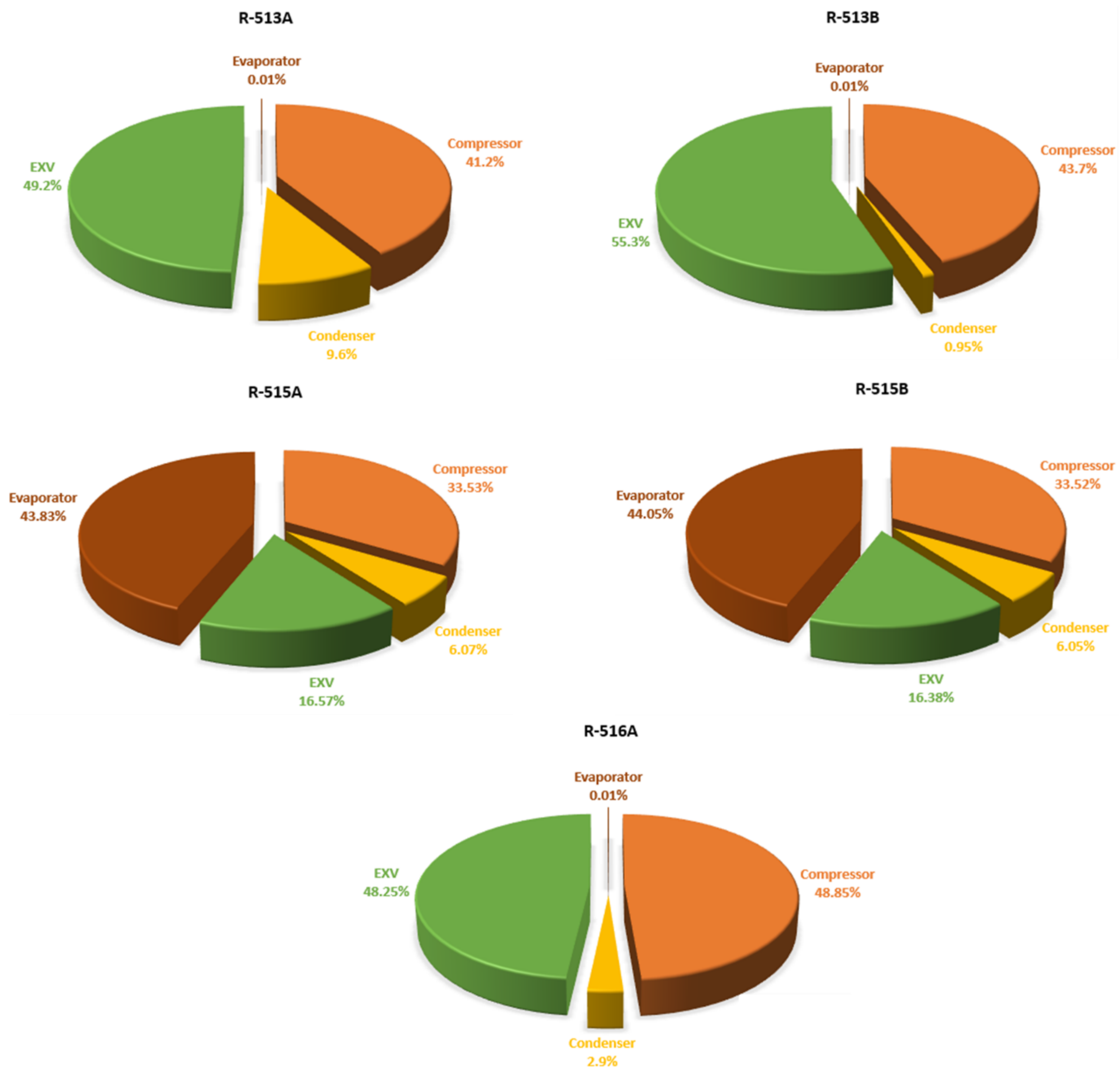

Fig. 6: Exergy destruction and efficiency for system components at $P_2 = P_{opt}$, $t_{evap} = 10$ ºC, $t_3 = 35$ ºC, and $\dot{m}_r = 0.075$ kg/s.

5.4. Systems' optimization

Table 5 presents optimal operating parameters—evaporator temperature, condenser pressure, and condenser outlet temperature for refrigerants R513A, R513B, R515A, R515B, and R516A at $\dot{m}_r = 0.075$ kg/s, aimed at maximizing performance and minimizing environmental impact. R513A and R513B operate at the highest evaporation ($P_1 = 0.501$ MPa) and condensation pressures ($P_2 = 0.70$ MPa), while R515A and R515B exhibit the lowest ($P_1 = 0.358$ MPa, $P_2 = 0.50$ MPa). R516A shows moderate pressures ($P_1 = 0.496$ MPa, $P_2 = 0.58$ MPa). R516A and R515B require the highest mass flow rates (0.0966 and 0.0969 kg/s, respectively), enhancing heat transfer but increasing system load, whereas R513A and R515A operate at lower rates (0.06146 and 0.0607 kg/s). R516A achieves the highest evaporator capacity ($\dot{Q}_{evap} = 16.54$ kW) and optimal COP (39.84), making it highly efficient for high-performance applications.

R515B follows with $\dot{Q}_{evap} = 16.05$ kW and COP = 20.21, while R513A and R513B show lower COPs (18.92 and 18.94, respectively) and cooling capacities, suitable for systems with limited pumping capacity. R516A's superior performance comes with higher mass flow rates, whereas R515A and R515B balance efficiency and lower outlet temperatures, making them suitable for efficiency-focused applications. The choice of refrigerant depends on specific system requirements, with R516A excelling in performance and R513A/R513B offering simplicity for low-demand systems.

Table 5: Comparisons of the studied refrigerants at optimal conditions (optimal COP).

Parameter	R-513A	R-513B	R-515A	R-515B	R-516A
P_1, P_4 (MPa)	0.501	0.501	0.358	0.358	0.496
P_2, P_3 (MPa)	0.70	0.70	0.50	0.50	0.58
t_1, t_4 (ºC)	15.0	15.0	15.0	15.0	15.0
t_2 (ºC)	28.58	28.52	26.71	26.76	21.46
t_3 (ºC)	20.0	20.0	20.0	20.0	20.0
$\dot{Q}_{evap}$ (kW)	12.28	12.22	12.28	12.42	12.84
$\dot{W}_{comp}$(kW)	0.649	0.645	0.609	0.615	0.322
γ	1.397	1.396	1.396	1.395	1.17
$COP_{optimal}$	18.92	18.94	20.14	20.21	39.84

6. Conclusions

This study highlights the potential of azeotropic refrigerant blends R513A, R513B, R515A, R515B, and R516A as eco-friendly, high-performance alternatives. Key findings include:

• R516A achieves the highest evaporator capacity ($\dot{Q}_{evap}$ = 10.7–11.18 kW) and optimal COP (39.84), making it ideal for high-capacity applications, although its higher compressor outlet temperature (t_2) may impact long-term reliability.

• R513A and R513B excel in energy efficiency, boasting the lowest compression ratio (γ) and highest COP (5.79–9.40), making them suitable for energy-saving systems. They also offer non-flammability (A1), enhancing safety compared to the moderately flammable R1234yf (A2L).

• R515A and R515B operate at lower pressures (P_1 = 0.358 MPa, P_2 = 0.50 MPa), reducing compressor stress, albeit with slightly lower efficiency, making them suitable for low-GWP applications.

R516A stands out for its superior cooling capacity and efficiency, while R513A/R513B prioritize safety and energy savings. These refrigerants offer improved COP, cooling capacity, and environmental performance over R1234yf, supporting the HVAC industry's transition to sustainable, efficient systems that align with global regulations. The study suggests that automotive manufacturers should use R513A and R513B in their air-conditioning systems due to their energy efficiency and safety classification. Fleet operators and original equipment manufacturers (OEMs) may find R515A and R515B beneficial due to their low operating pressures. Component designers and HVAC engineers should develop heat exchangers and compressor topologies to accommodate the thermodynamic characteristics of any refrigerant. Policymakers and environmental regulatory authorities can facilitate the implementation of low-GWP azeotropic blends by creating incentives or regulations aligned with international climate treaties, such as the Kigali Amendment. These steps encourage a smooth transition towards more eco-friendly, efficient, and sustainable cooling solutions.

Acknowledgments

This work was funded by the University of Jeddah, Jeddah, Saudi Arabia, under grant No. (UJ-23-DR-107). Therefore, the authors thank the University of Jeddah for its technical and financial support.

Nomenclature

$\dot{E}$	exergy (kW)
h	specific enthalpy (kJ/kg)
$\dot{I}$	exergy destruction (kW)
$\dot{m}$	mass flow rate (kg/s)
P	Working fluid pressure (MPa)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
t	temperature (°C)
T	temperature (K)
$\dot{W}$	power (kW)

Greek symbols

η	efficiency
γ	compressor pressure ratio

Subscripts

cond	condenser
comp	compressor
cv	control volume
en	energy

ex	exergy
evap	evaporator
i= 1, 2, 3, 4	index referring to various positions in the system
in	inlet
is	isentropic e
j	boundary
max	maximum
o	outlet
r	refrigerant
ref	refrigeration
0	Environmental state
1,2,3, ……	working fluid state points

Abbreviations

AAC	automotive air-conditioning
COP	coefficient of performance
EXV	Expansion valve
GWP	global warming potential
HFC	Hydrofluorocarbon
HFO	Hydrofluro-Olefins
ODP	ozone depletion potential

References

[1] UNEP, United Nations Environment Programme, Montreal Protocol on Substances that Deplete the Ozone Layer, Final Act. United Nations, New York, 1987.

[2] GCRP, Global Environmental Change Report, A brief analysis kyoto protocol, 1997.

[3] UNEP, United Nations Environment Programme, Twenty-eighth meeting of the parties to the Montreal Protocol on substances that deplete the ozone layer, Decision XXVIII/Further Amendment Montreal Protocol, 2016, pp. 1–9.

[4] Khalid A. J., et al., Experimental and computer performance study of an automotive air conditioning system with alternative refrigerants, Energy Conversion and Management, *44* (2003), 18, pp. 2959-2976.

[5] Baskaran A., Koshy P., Mathews, A Performance Comparison of Vapour Compression Refrigeration System Using Eco Friendly Refrigerants of Low Global Warming Potential, Engineering, Environmental Science (2012).

[6] Yohan L., et al., Performance of virtually non-flammable azeotropic HFO1234yf/HFC134a mixture for HFC134a applications, International Journal of Refrigeration, *36* (2013),14, pp. 1203-1207.

[7] Ioan S., A review on substitution strategy of non-ecologicalrefrigerants from vapour compression-based refrigeration,air-conditioning and heat pump systems, International Journal of Refrigeration, *46* (2014), pp. 123-141.

[8] Adrián M., et al., Experimental assessment of R134a and its lower GWPalternative R513A, International Journal of Refrigeration, *74* (2017), pp. 682-688.

[9] Uwadiae M. E., et al., Experimental Investigation of R-134a And R 600a Refrigerant Blend In Domestic Vapour Compression Refrigeration System, Nigerian Journal of Technology (NIJOTECH) *36* (2017), pp. 1138 – 1144.

[10] Daviran S., et al., A comparative study on the performance of HFO-1234yfand HFC-134a as an alternative in automotive air conditioning systems, Applied Thermal Engineering, *110* (2017), pp. 1091-1100.

[11] Yang M., et al., Experimental study on R1234yf/R134a mixture (R513A) asR134a replacement in a domestic refrigerator, Applied Thermal Engineering, *146* (2019), pp. 540-547.

[12] Mota-Babiloni A., et al., Experimental exergy analysis of R513A to replace R134a in a small capacity refrigeration system, Energy, *162* (2018), pp. 99-110.

[13] Dong W., et al., Energy and exergy analysis of an air-source heat pump water heater system using CO /R170 mixture as an azeotropy refrigerant for sustainable development, International Journal of Refrigeration, *106* (2019), pp. 628-638.
[14] Yu B., et al., Experimental energetic analysis of CO /R41 blends in automobile air-conditioning and heat pump systems, Applied Energy, *239* (2019), pp. 1142-1153.
[15] Sun J., et al., Energy and exergy analyses of R513a as a R134a drop-in replacement in a vapor compression refrigeration system, International Journal of Refrigeration, *112* (2020), pp. 348-356.
[16] Mota-Babiloni A., et al., Experimental influence of an internal heat exchanger (IHX)using R513A and R134a in a vapor compression system, Applied Thermal Engineering, *147* (2019), pp. 482-491.
[17] Direk M., et al., Experimental Investigation of an Automotive Air Conditioning System Using R444A and R152a Refrigerants as Alternatives of R134a, Journal of Mechanical Engineering, *65* (2019), pp. 212-218.
[18] Maalem Y., et al., Performance analysis of ternary azeotropic mixtures indifferent vapor compression refrigeration cycles, International Journal of Refrigeration, *119* (2020), pp.139-151.
[19] Alhendal Y., et al., Thermal Performance Analysis of Low-GWP Refrigerants in Automotive Air-Conditioning System, Advances in Materials Science and Engineering, *14* (2020), pp. 1-14.
[20] Abid U., Parametric study of absorption refrigeration with vapor compression refrigeration cycle using wet, isentropic and azeotropic working fluids: Conventional and advanced exergy approach, Energy, *201* (2020), pp. 117491.
[21] Zhang N., Dai Y,, Performance evaluation of alternative refrigerants for R134a in automotive air conditioning system, Asia-Pac J Chem Eng., *17* (2022), pp. 2732
[22] Li G., Performance evaluation of low global warming potential working fluids as R134a alternatives for two-stage centrifugal chiller applications, Korean J. Chem. Eng., *38* (2021), 7, pp. 1438-1451.
[23] Velasco F. J. S., et al., Energy efficiency evaluation of the use of R513A as a drop-in replacement for R134a in a water chiller with aminichannel condenser for air-conditioning applications, Applied Thermal Engineering, *182* (2021), pp. 115915.
[24] Liu B., et al., Evaluation of a low-GWP and nonflammable blend as anew alternative for R134a in the heat pump system, International Journal of Refrigeration, *143* (2022), pp. 1-10.
[25] İşkan Ü., Direk M., Experimental performance evaluation of the dual-evaporator ejector refrigeration system using environmentally friendly refrigerants of R1234ze(E), ND,R515a, R456a, and R516a as a replacement for R134a, Journal of Cleaner Production, *352* (2022), pp. 131612
[26] Zhang N., et al., Study on environmentally friendly refrigerant R13I1/R152a as an alternative for R134a in automotive air conditioning system, Chinese Journal of Chemical Engineering, *44* (2022), pp. 292-299.
[27] Molinaroli L., et al., Drop-in analysis of R450A and R513A as low-GWP alternatives to R134a in a water-to-water heat pump, International Journal of Refrigeration, *135* (2022), pp. 139-147.
[28] Belman-Flores J. M., et al., Experimental evaluation of R513A as a low GWP refrigerant to replace R134a in a domestic refrigerator, International Journal of Refrigeration, *142* (2022), pp. 148-155.
[29] Ojeda F. W. A. B., et al., Experimental evaluation of low-GWP refrigerants R513A, R1234yf and R436A as alternatives for R134a in a cascade refrigeration cycle with R744, International Journal of Refrigeration, *144* (2022), pp. 175-187.
[30] İşkan Ü., Direk M., Experimental performance evaluation of the dual-evaporator ejector refrigeration system using environmentally friendly refrigerants of R1234ze(E), ND, R515a, R456a, and R516a as a replacement for R134a, Journal of Cleaner Production, *352* (2022), pp. 131612.
[31] Al-Sayya A. K. S., et al., Comprehensive experimental evaluation of R1234yf-based low GWP working fluids for refrigeration and heat pumps, Energy Conversion and Management, *258 (*2022), pp. 115378.

[32] Li S., et al., Comparative performance of ternary azeotropic mixtures as substitutes for R134a in dual-temperature air source heat pump combined ejector, Thermal Science and Engineering Progress, *37* (2023), pp. 101577.

[33] Méndez D et al., Experimental energy evaluation of R516A and R513A as replacement of R134a in refrigeration and air conditioning modes, International Journal of Refrigeration, *154* (2023), pp. 73-83.

[34] Kuwar Y. V., Performance evaluation of ecofriendly R1234ze(E) refrigerant in an automotive air conditioning system, Heat Transfer, *53* (2024), pp. 472–494.

[35] Sharif M. Z., et al., Performance improvement strategies of R1234yf in vapor compression refrigeration system as a R134a replacement: A review, Journal of the Taiwan Institute of Chemical *148* (2023), pp. 105032.

[36] Dagıdır K., Bilen K., Usage of R513A as an alternative to R134a in a refrigeration system: An experimental investigation based on the Kigali amendment, International Journal of Thermofluids, *21* (2024), pp. 100582.

[37] Sun D., et al., Experimental and simulation study on R134a/RE170/R152 a mixture as R134 a replacement in a moderately-high temperature heat pump, Applied Thermal Engineering, *236* (2024), pp. 121643.

[38] Conte R., et al., Experimental investigation of large scroll compressors working with six low-GWP refrigerants, Thermal Science and Engineering Progress, *44* (2023), pp. 102043.

[39] Yıldırım R., Şahin A. Ş., Prediction of energy and exergy performance for subcooled and superheated vapor compression refrigeration system working with new generation refrigerants, Sustainable Energy Technologies and Assessments, *57* (2023), pp. 103177.

[40] Al-Sayyab A. K. S., et al., Energy, exergy, and environmental (3E) analysis of a compound ejector-heat pump with low GWP refrigerants for simultaneous data center cooling and district heating, International Journal of Refrigeration, *133* (2022), pp. 61-72.

[41] Zhao X., et al., Optimization and exergoeconomic analysis of a solar-powered ORC-VCR-CCHP system based on a ternary refrigerant selection model, Energy, *290* (2024), pp. 129976.

[42] Wang J., et al., Review on the trend of ultra-low-GWP working fluids for small-capacity vapour-compression systems, Sustainable Energy Technologies and Assessments, *66* (2024), pp. 103803.

[43] ASHRAE Standard 34, ANSI/ASHRAE Standard 34-2022, Designation and Safety Classification of Refrigerants, Refrigeration and Air-Conditioning Engineer Incorporation, Atlanta, GA, USA, 2016.

[44] Liao S. M., et al., A correlation of optimal heat rejection pressures in transcritical carbon dioxide cycles, Applied Thermal Engineering, *20* (2000), pp. 831–841.

[45] Aspen HYSYS V12.1. 2021. Available online: www.aspentech.com (accessed on 1 May 2023).

[46] SAE International. (2008). SAE J2765: Procedure for Measuring System Capacity of Mobile Air Conditioning Systems. Warrendale, PA: SAE International.

[47] Mota-Babiloni A., et al., Experimental assessment of R134a and its lower GWP alternative R513A, International Journal of Refrigeration, *74* (2017), pp. 682-688.

Paper submitted: 11.04.2025
Paper revised: 20.05.2025
Paper accepted: 26.05.2025