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THEORETICAL PERFORMANCE EVALUATION OF THE NEW ZEOTROPIC REFRIGERANT R457B AND ITS BLENDS IN A VAPOR COMPRESSION REFRIGERATION CYCLE

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Abstract. *Refrigerants with low global warming potential (GWP) are widely studied for application in refrigeration systems. However, refrigerants with high GWP have been broadly used in heating, ventilation, air conditioning and refrigeration systems (HVAC-R). As evidenced in the Paris Agreement, there is an estimated increase of approximately two degrees celsius in the temperature of the globe. Thus, in order to ensure a sustainable development of the refrigeration area, this paper presents an energy and exergy analysis of the new zeotropic refrigerant R457B and it's blends in a vapor compression refrigeration system. The main goal is to analyze the drop-in possibility of R134a and for this purpose the First and Second Law of Thermodynamics are applied. The simulation is carry out in MATLAB, where performance and flammability are analyzed. The selected blends have GWP and RF (refrigerant flammability) lower than 150 and 30 kJ/g. All the refrigerants reduced the coefficient of performance (COP) when compared to R134a, nevertheless, RGTB4 (R32/1234yf/152a wt% of 3.0/35.0/62.0) reduced the COP by only 1.4%. In addition, although RGTB4 led to a 2.9% drop in volumetric refrigeration capacity, GWP was reduced by around 13 times compared to R134a, making it a suitable blend for drop-in.*

Keywords: *blend, COP, GWP, RF, temperature.*

1. INTRODUCTION

For several years ozone depleting refrigerants have been used as essential components in refrigeration systems. However, scientists have discovered that their properties, in contact with ozone (O_3), contribute to the formation of chlorine monoxide, gas responsible for the destruction of the ozone layer (Rowland, 1990; Murthy *et al.*, 2019). As a result, halogenated chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have had their use restricted through the Montreal Protocol, established by the United Nations (UN) in 1987. The urgent need to control the destruction of the ozone layer has become evident due to the consequences that UV rays have on humans and the environment. Excess contact with UV rays, in particular UVB, causes burns, skin aging, and stimulates cataract. Furthermore, the change in UV incidence affects phytoplankton, which is responsible for absorbing more than half of the carbon dioxide emissions. (Tevini *et al.*, 1993; Jin *et al.*, 2023).

With Ozone Depletion Potential (ODP) equal to zero, hydrofluorocarbons (HFCs) have emerged as a proposal to replace CFCs and HCFCs. However, despite the wide application and excellent performance of HFCs in heating, ventilation, air conditioning and refrigeration systems (HVAC-R), the problem with global warming only gets worse over time (Shaik *et al.*, 2022). In order to supply the increasing human demand, industrial advances have accelerated the warming process of the planet. Small dust particles once considered only as an urban problem are now able to cross the seas carried by plumes of Atmospheric Brown Clouds (ABCs). These particles absorb and reflect the sunlight, which delays the hydrological cycle. The carbon and some organic compounds absorb the solar radiation, which raises the temperature of the globe. This phenomenon is known as the Greenhouse Effect, and is caused by Greenhouse Gases (GHGs) (Ramanathan and Feng, 2009; Subramanian *et al.*, 2020).

In an attempt to reduce the impacts caused by the greenhouse effect, the Kyoto protocol, proposed in 1997, aims to reduce the use of refrigerants with high Global Warming Potential (GWP) (Tarabkhah *et al.*, 2023). It is estimated that refrigeration services in industry are responsible for more than 10% of GHGs emissions (Dong *et al.*, 2021). R134a has a 100-year GWP of 1430, which makes it a target in emission control (Meng *et al.*, 2018). Through the EU F-Gases Regulation and European mobile air-conditioner directives, refrigerants with GWP greater than 150 have been banned from use in manufactured vehicles since 2017 (Cho *et al.*, 2013; Zhang *et al.*, 2022).

Looking for a replacement of R134a, a lot of research has been done to keep performance and sustainability tied up in HVAC-R devices. In an experimental study, Aprea *et al.* (2017) analyzed the performance of the R1234yf/R134a (10/90% weight) blend as an alternative to R134a in a domestic refrigerator. The results showed that the R1234yf/R134a blend is a good drop-in for R134a. Ojeda *et al.* (2022) studied the possibility of replacing R134a with low-GWP refrigerants in a cascade refrigeration cycle. R1234yf showed a 3.7% reduction in the coefficient of performance (COP). In another study, Soni *et al.* (2022) performed a comparative analysis of R1234yf, R1234ze, R717 and R600a refrigerants in a vapor compression refrigeration system aiming to replace R134a. R1234yf is the refrigerant that showed the lowest pressure ratio, however, there was a slight increase in power consumption.

Having a GWP of 124 and ODP equal to zero, R152a is an HFC with great application in HVAC-R systems. Longo *et al.* (2019) tested the heat transfer and pressure drop of R152a, R1234yf, and R1234ze(E) refrigerants. The results showed similar performance to R134a. In a comparative study, Vaghela (2017) analyzed the drop-in of R134a by R290, R600a, R407C, R410A, R404A, R152a and R1234yf refrigerants in an Automobile Air-Conditioning system (AACs). R152a and R1234yf showed the highest and lowest COP, respectively. Also according to the authors, the substitution of R1234yf is more suitable because it provides the least modification in AACs.

Li and Tang (2022) studied the possibility of drop-in of R134a by low GWP blends in a Mobile Air-Conditioning system. Binary pairs of the refrigerants R134a, R1234yf, R1234ze(E), R32, R227ea, and R152a were analyzed. R152a/R134a, R152a/R1234yf, and R32/R152a had higher capacity and COP than R134a, however, R32, R152a, and R1234yf are flammable, which is a parameter to be considered.

As evidenced in the Paris Agreement, there is an estimated increase of approximately two degrees celsius in the temperature of the globe. Hence, in order to ensure a sustainable development of the refrigeration area, this paper presents an energy and exergy analysis of the new zeotropic refrigerant R457B in a vapor compression refrigeration system. The main goal is to analyze the drop-in possibility of R134a, and for this purpose, the power consumed by the compressor, volumetric refrigeration capacity, discharge temperature, pressure ratio, mass flow rate and coefficient of performance are evaluated. Second law analysis is conducted by evaluating exergy destruction and exergy efficiency. In addition to R457B, the refrigerant R457A and some blends are analyzed. The blends are performed by changing the weight percentage of the refrigerants R32, R1234yf and R152a, which compose R457B and R457A. The simulation is carry out in MATLAB, where subcooling and superheating are considered, as well as the isentropic, mechanical, and electrical efficiency of the compressor. Pressure drops are evaluated in the evaporator, condenser, suction and discharge valve, and suction and discharge line. The flammability is measured using RF-number.

2. GLOBAL WARMING POTENTIAL

The average global warming potential of the refrigerants blends are calculated by the Eq. (1) (Li and Tang, 2022).

$$GWP_B = \frac{w_1 GWP_1 + w_2 GWP_2 + ...}{w_1 + w_2 + ...} = \sum_i w_i GWP_i \cdot \left(\sum_i w_i\right)^{-1} \tag{1}$$

where GWP_B is the global warming potential of the blend; w_i is the weight fraction of ith component; GWP_i is the GWP of the ith component.

3. REFRIGERATION FLAMMABILITY NUMBER

Kondo *et al.* (2002) generated a mathematical expression, represented in Eq. (2), known as the RF-number, which can provide the flammability class of a refrigerant. Blends with RF-number below 30 kJ/g are considered medium flammable, between 30 and 150 kJ/g are classified as flammable, and above 150 kJ/g as highly flammable.

$$RF_B = \left[\left(\frac{UFL}{LFL}\right)^{0.5} - 1\right] \frac{HC}{M} \tag{2}$$

where RF_B is the refrigerant flammability of the blend; UFL is the upper flammability limit (vol.%); LFL is the lower flammability limit (vol.%); HC is the heat of combustion (kJ/kmol); M is the molecular weight (g/kmol).

4. THERMODYNAMICS ANALYSIS

4.1 Cycle

The thermodynamic analysis of the vapor compression refrigeration cycle is performed based on the thermodynamic cycle represented in Fig. 1. The state points are described in Tab. 1 (Arora, 2009). The thermal properties of the mixtures are obtained by REFPROP 8.0 (Lemmon *et al.*, 2007).

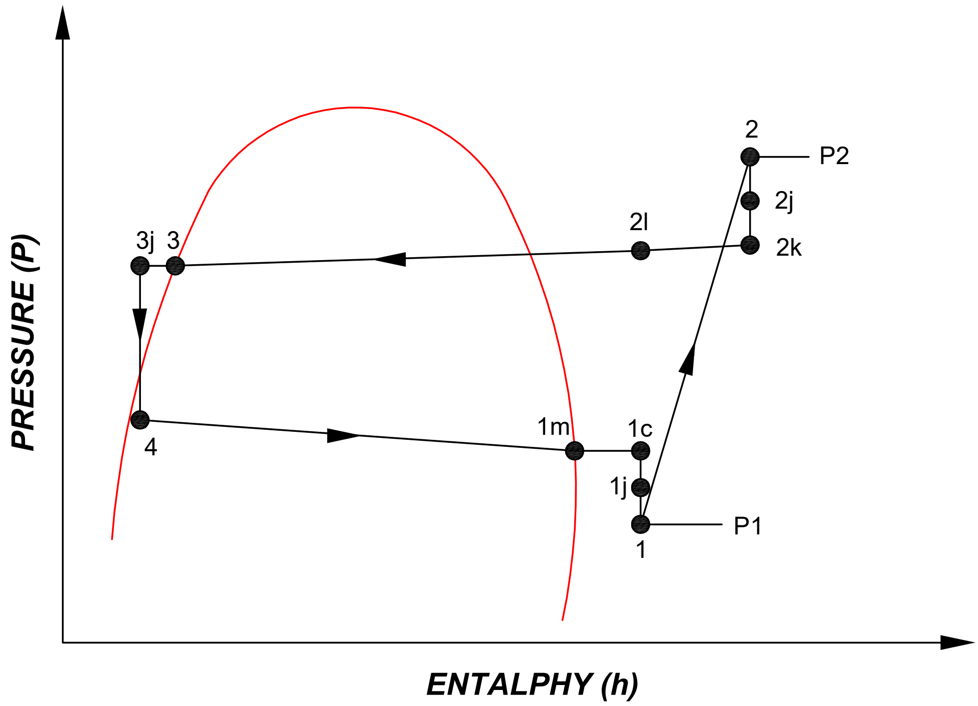

Figure 1. Practical P-h diagram of a Vapour Compression Refrigeration cycle.

Table 1. Description of states in the Vapour Compression Refrigeration cycle.

Points	**Description of states**
1m-1c	Superheating in the evaporator
1c-1k	Heat gain and superheating in the suction line
1k-1j	Suction line pressure drop
1j-1	Pressure drop in the suction valve
1-2	Compression
2-2j	Pressure drop in the discharge valve
2j-2k	Pressure drop in the discharge line
2k-2l	Heat loss and desuperheating in the discharge line
2k-3	Pressure drop in the condenser
3-3j	Subcooling in the condenser
3j-3k	Heat gain in the liquid line
3k-4	Expansion
4-1m	Pressure drop in the evaporator

4.2 Conditions

The conditions are steady state, adiabatic compressor and expansion valve, and negligible kinetic and potential energy variation. Furthermore, the condensing and evaporating temperatures are set according to the AHRI standard 540 refrigeration cycle (54.4°C and 7.2°C, respectively). Subcooling and superheating are equal to 8.3°C and 11.1°C, respectively; the isentropic and mechanical efficiency of the compressor are equal to 75% and 90%, respectively; and the motor electrical efficiency is 90%. The ambient temperature is 25°C, and the refrigeration capacity is 1kW (Standard, 2015; Shaik *et al.*, 2020).

The pressure drops are shown in the Tab. 2 (Shaik *et al.*, 2020). The temperature rise before the compressor and expansion valve inlet are neglected, so 3k = 3j and 1k = 1c.

4.3 Energy

The energy equations are calculated based on the First Law of Thermodynamics applied to states. For the thermodynamic cycle expressed in Fig. 1, the energy equations are expressed below (Çengel *et al.*, 2020; Bolaji, 2020).

Table 2. Pressure drops.

Pressure drop (bar)	**Description**
0.1	Pressure drop in the suction line
0.1	Pressure drop in the discharge line
0.2	Pressure drop in the suction valve
0.4	Pressure drop in the discharge valve
0.1	Pressure drop in the evaporator
0.25	Pressure drop in the condenser

The compressor work (kJ/kg) is measured by:

$$W_c = \frac{W_s}{\eta_s} = \frac{h_{2s} - h_1}{\eta_s} \tag{3}$$

where W_s is the isentropic compressor work, η_s is the isentropic efficiency, and h is the entalphy of the state described by the subscriptions.

The refrigeration effect (kJ/kg) is calculated by:

$$RE = (h_{1c} - h_4) \tag{4}$$

The pressure ratio is given by:

$$P_r = \frac{P_c}{P_e} \tag{5}$$

where P_c is the pressure in the condenser and P_e the pressure in the evaporator.

The volumetric refrigeration capacity (kJ/m^3) is calculated by:

$$VRC = \frac{h_{1c} - h_4}{v_{1c}} \tag{6}$$

where v_{1c} is the specific volume at the evaporator outlet.

The mass flow rate (kg/s) is given by:

$$\dot{m} = \frac{\dot{Q}_L}{h_{1c} - h_4} \tag{7}$$

where $\dot{Q}_L$ is the refrigeration capacity (kW).

The electric power (kW) is measured by:

$$\dot{W}_{elet} = \frac{\dot{m} W_c}{\eta_{mech} \eta_{elet}} \tag{8}$$

where η_{mech} is the compressor mechanical efficiency and η_{elet} is the motor electric efficiency.

The coefficient of performance is calculated by:

$$COP = \frac{(h_{1c} - h_4)}{(h_2 - h_1)} \tag{9}$$

The energy efficiency ratio is given by:

$$EER = \frac{\dot{m}(h_{1c} - h_4)}{\dot{W}_{elet}} \tag{10}$$

4.4 Exergy

Associated with the irreversibilities of a system, the exergy destruction (given in kJ/kg) can be calculated by applying the Second Law of Thermodynamics (Eq. 11) on each component (Çengel *et al.*, 2020).

$$\sum \left(1 - \frac{T_0}{T_i}\right) Q_i - W + \sum_{in} \psi - \sum_{out} \psi - \chi_{dest} = d\chi_{cv} \tag{11}$$

where T_0 is the dead state temperature, T_i the temperature of the condenser or evaporator, Q_i the heat of the condenser or evaporator, W the boundary work, χ_{dest} the exergy destroyed in the component, $d\chi_{cv}$ the exergy variation in the system, and ψ is given by:

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \tag{12}$$

where s is the entropy, $V^2/2$ the kinetic energy and gz the potential energy.

For the compressor:

$$\chi_{comp} = (h_1 - T_0 s_1) - (h_2 - T_0 s_2) + W_{elet} \tag{13}$$

For the condenser:

$$\chi_{cond} = (h_2 - T_0 s_2) - (h_{3j} - T_0 s_{3j}) - Q_{cond}\left(1 - \frac{T_0}{T_c}\right) \tag{14}$$

where Q_{cond} is given by:

$$Q_{cond} = (h_2 - h_{3j}) \tag{15}$$

For the expansion valve:

$$\chi_{val} = (s_4 - s_{3k})T_0 \tag{16}$$

For the evaporator:

$$\chi_{eva} = (h_4 - T_0 s_4) - (h_{1c} - T_0 s_{1c}) + RE\left(1 - \frac{T_0}{T_e}\right) \tag{17}$$

The exergetic efficiency is given by the equation 18.

$$\eta_{II} = \frac{COP}{COP_{rev}} \tag{18}$$

where COP_{rev} is Carnot coefficient of performance.

4.5 Analyzed blends

The refrigerants that compose R457B and R457A are R32, R1234yf and R152a. The properties of these refrigerants, including R134a, are shown in Tab. 3.

Table 3. Properties of the refrigerants.

Refrigerant	**Weight (g/mol)**	**Boiling point (°C)**	**P_c (MPa)**	**T_c (°C)**	**GWP**	**Safety group**
R134a	102.03	-26.07	4.06	101.06	1430	A1
R32	52.02	-51.65	5.78	78.11	677	A2
R1234yf	114.04	-29.45	3.38	94.70	4	A2L
R152a	66.05	-24.02	4.52	113.26	138	A2

Aiming to achieve a better solution in terms of enviroment, four blends are selected in a way that their weight percentage results in a GWP less than 150. The blends are disposed in Tab. 4, where RGTB means Refrigerant Blend.

Table 4. Composition and safety classification of the studied refrigerant blends.

Refrigerant	**Composition**	**Weight (%)**	**GWP$_B$**	**RF$_B$**	**Safety group**
R134a	-	-	1430	-	A1
R457A	R-32/1234yf/152a	(18.0/70.0/12.0)	141	5.6	A2
R457B	R-32/1234yf/152a	(35.0/55.0/10.0)	253	5.5	A2
RGTB1	R-32/1234yf/152a	(10.0/45.0/45.0)	132	8.3	A2
RGTB2	R-32/1234yf/152a	(05.0/60.0/35.0)	85	7.3	A2
RGTB3	R-32/1234yf/152a	(05.0/35.0/60.0)	118	9.7	A2
RGTB4	R-32/1234yf/152a	(03.0/35.0/62.0)	107	9.8	A2

5. ALGORITHM VALIDATION

For validation of the algorithm, simulations are performed for R22 at evaporation temperature of -15°C, and condensing temperature ranging between 35°C and 55°C, with intervals of 10°C. The pressure drop in the evaporator is 0.2 bar, and in the condenser 0.1 bar. The subcooling and superheating are 5°C, and the isentropic compressor efficiency is equal to 75%. The results are showed in Table 5. A deviation of less than 1% is observed.

Table 5. Validation of the algorithm with the literature for R22 and evaporation temperature of -15°C (Shaik *et al.*, 2020).

	Condensing temperature (T_{cond}) = 35/45/55°C		
Parameters	Literature for R22	Algorithm for R22	Deviation (%)
RE (kJ/kg)	165,11/152,08/138,48	165,96/152,97/139,45	-0,51/-0,58/-0,70
W_c (kJ/kg)	55,73/65,01/73,72	55,51/64,74/73,59	0,39/0,41/0,17
COP	2,962/2,339/1,878	2,989/2,362/1,894	-0,91/-0,98/-0,85
P_r	4,572/5,836/7,341	4,573/5,838/7,343	-0,02/-0,03/-0,02

6. RESULTS AND DISCUSSION

Figure 2 shows the variation of volumetric refrigeration capacity. Since the specific volume in the vapor phase is inversely proportional to the VRC, a low specific volume provides high volumetric refrigeration capacity. For evaporating and condensing temperatures of 7.2°C and 54.4°C, respectively, R457A, R457B and RGTB1 increased the VRC by 13.2%, 32.7% and 3.3%, respectively, while RGTB2, RGTB3 and RGTB4 reduced it by 0.9%, 1.3% and 2.9%, respectively. Once the recommendation for drop-in is a reduction of no more than 10% in the VRC, the refrigerants are well suited to replacing R134a.

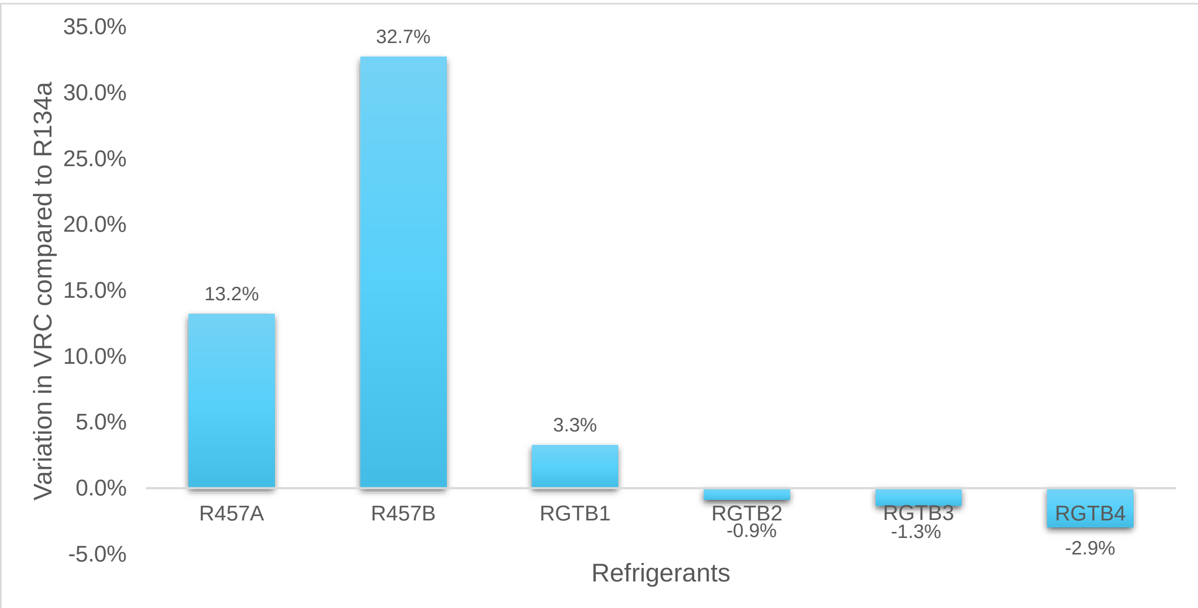

Figure 2. Variation in volumetric refrigeration capacity compared to R134a.

The variation in compressor discharge temperature is represented in Fig. 3. The compressor discharge temperature increased by 6.7%, 19.1%, 10.7%, 2.8%, 10.5% and 9.0% for R457A, R457B, RGTB1, RGTB2, RGTB3 e RGTB4, respectively. Despite the large increase by R457B, RGTB1, RGTB3 and RGTB4, the discharge temperature did not exceed 100°C, so the temperature will probably not affect the components of the compressor. All analyzed refrigerants had similar pressure ratios to R134a. R457A, R457B, RGTB1 and RGTB3 increased the pressure ratio by 1.7%, 4.4%, 2.8% and 1.1%, respectively, while RGTB2 and RGTB4 reduced the pressure ratio by 1.0% and 0.2%, respectively.

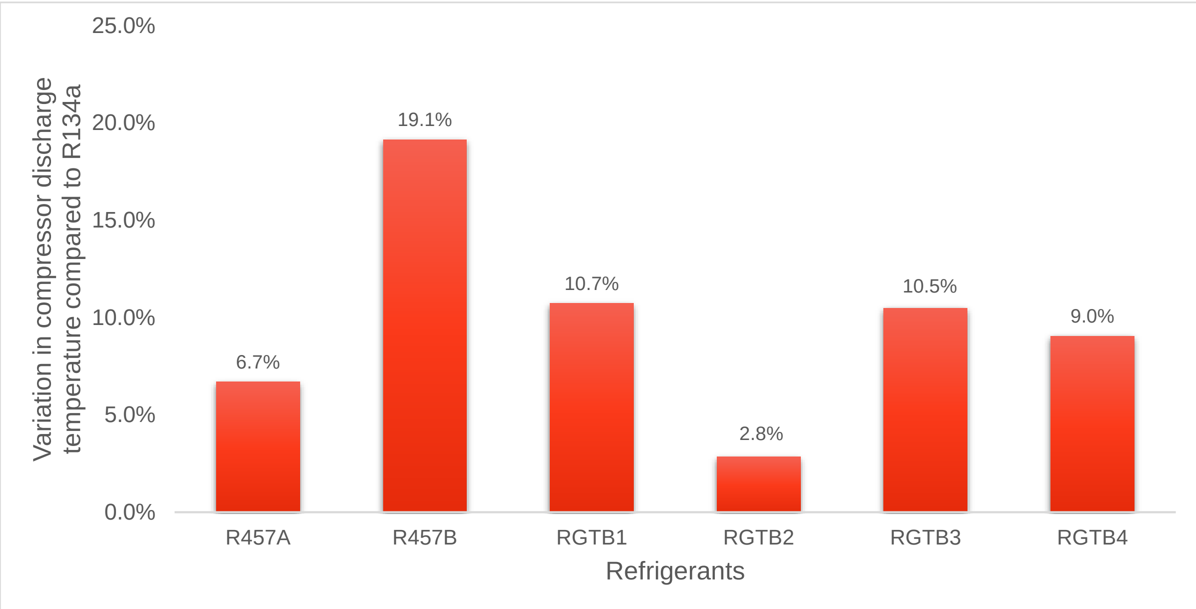

Figure 3. Variation in compressor discharge temperature compared to R134a.

The mass flow rate is show in Fig. 4. R457A, R457B, RGTB1, RGTB2, RGTB3 and RGTB4 dropped the mass flow rate by 4.3%, 15.4%, 20.2%, 10.8%, 25.2% and 25.1%, respectively. The density in the liquid phase is related to the refrigerant charge applied in the system. Thus, low density provides low charge, which implies in cost reduction. In addition, low density reduces the pressure drop across the expansion valve, which avoids a decrease in COP due to the increase in compressor work.

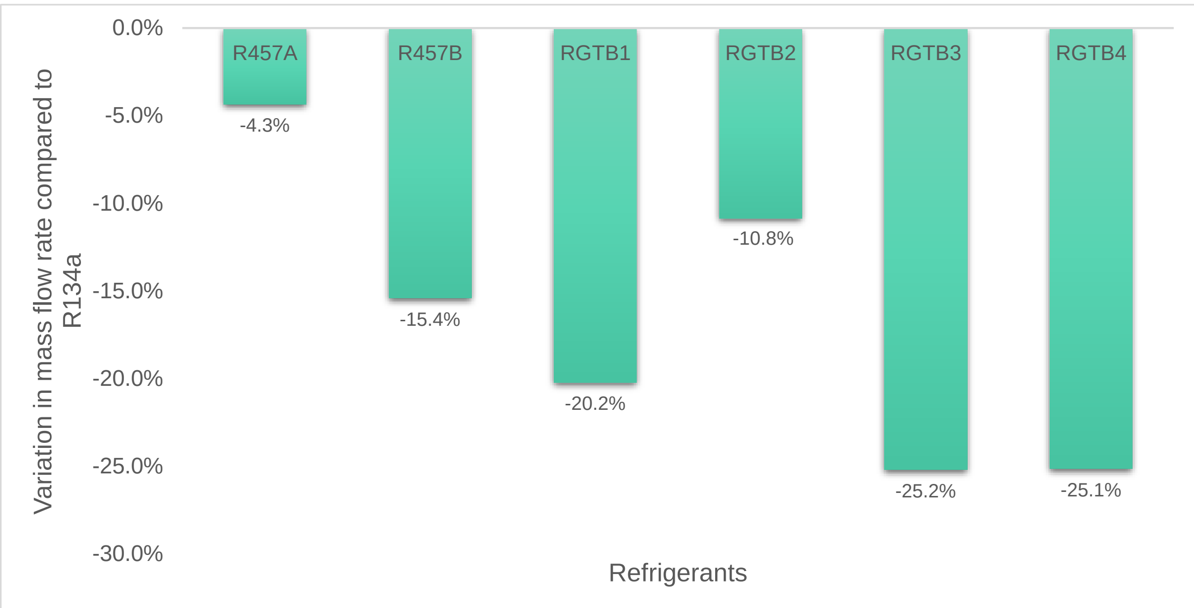

Figure 4. Variation in mass flow rate compared to R134a.

The COP is represented in Fig. 5. It is observed that COP was reduced in 7.9%, 10.7%, 5.1%, 3.2%, 2.5% and 1.4%, for R457A, R457B, RGTB1, RGTB2, RGTB3 and RGTB4, respectively. The increase in compressor work is 13.5%, 32.4%, 32.1%, 15.9%, 37.2% and 35.5% for the refrigerants cited above. Although the refrigerants have increased the compressor work, there has been an increase in the refrigeration effect of 4.5%, 18.2%, 25.3%, 12.2%, 33.7% and 33.6% for the same refrigerants. In this sense, though the recommendation for drop-in is an increase in compressor work of approximately 6.0%, the relationship in the conversion of compressor work to refrigeration effect is higher for RGTB3 and RGTB4. This can also be observed from the energy efficiency ratio and the exergetic efficiency (Tab. 6), where the performance obtained is close to R134a.

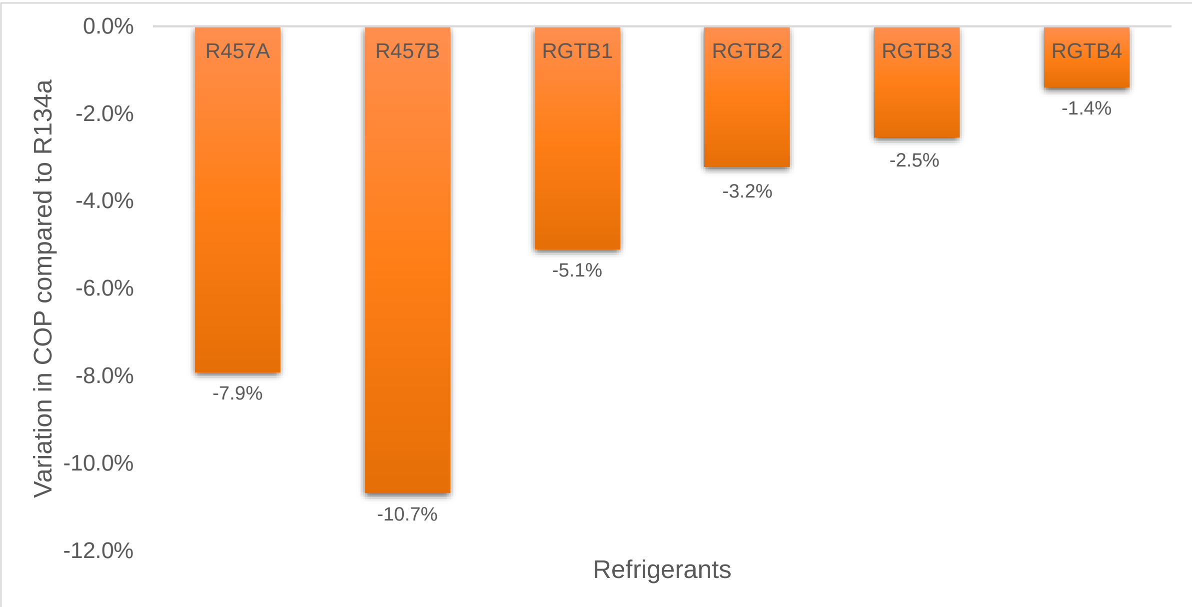

Figure 5. Variation in coefficient of performance compared to R134a.

Table 6. Energy efficiency ratio and exergetic efficiency for 7.2°C and 54.4°C.

Refrigerant	**R134a**	**R457A**	**R457B**	**RGTB1**	**RGTB2**	**RGTB3**	**RGTB4**
EER	2.69	2.48	2.40	2.55	2.60	2.62	2.65
η_{II} (%)	21.1	19.4	18.9	20.0	20.4	20.6	20.8

The percentage increase in total exergy destruction compared to R134a is shown in Tab. 7. All refrigerants had greater exergy destruction than R134a.

Table 7. Percentage increase in total exergy destruction compared to R134a.

Refrigerant	**R457A**	**R457B**	**RGTB1**	**RGTB2**	**RGTB3**	**RGTB4**
Total exergy destruction (%)	22.8	47.6	38.6	19.3	40.3	36.9

The exergy destruction in each component related to the total exergy destruction is shown in Fig. 6. It is observed that the compressor is the device that destroys the most exergy, followed by the expansion valve, condenser and evaporator. The compressor requires electrical energy to compress the refrigerant, so part of this energy is transformed into mechanical work, while another part is lost due to the irreversibilities of the device. In the expansion valve the process is different, since the refrigerant is throttled to promote a drop in pressure and temperature. This operation must be conducted carefully, since it has a direct impact in the power consumed by the compressor.

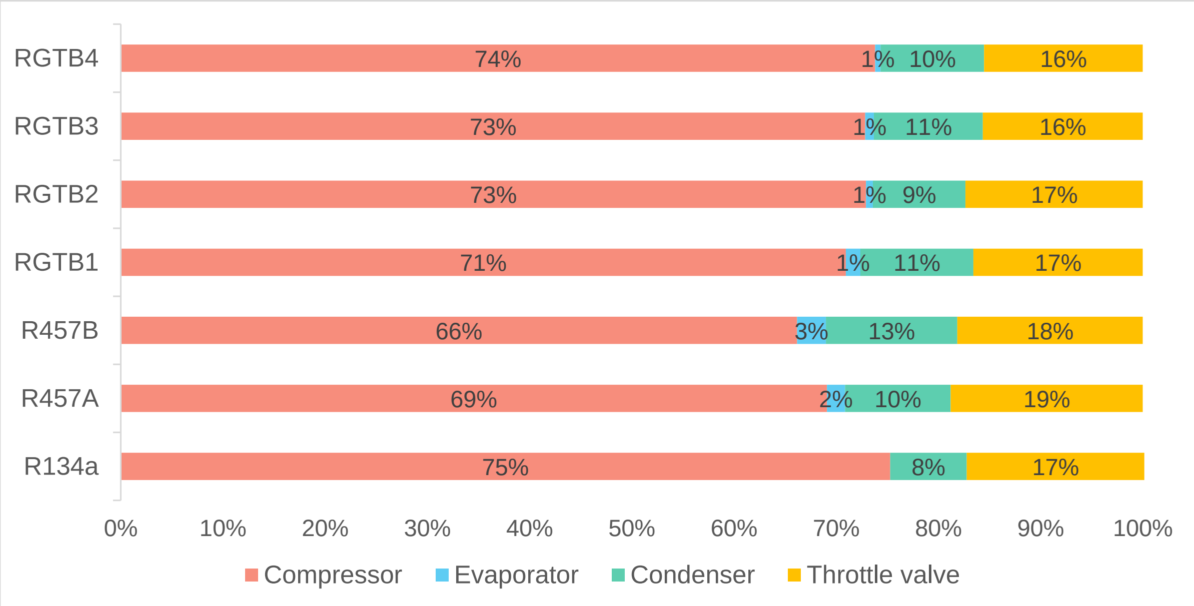

Figure 6. Percentage of exergy destruction in each component.

The change in the coefficient of performance with evaporator temperature is shown in Fig. 7. It is observed that below -8.5°C, RGTB4 provides a slightly higher COP than R134a, which can be useful for some applications.

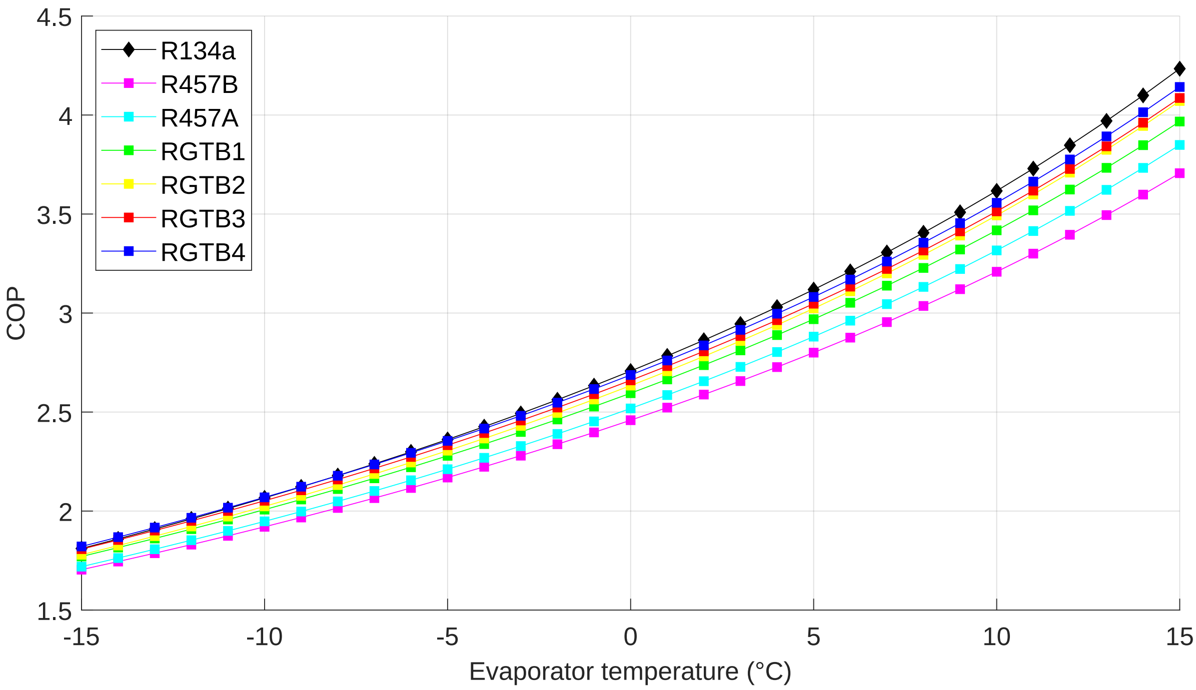

Figure 7. Coefficient of performance for T_c equal to 54.4°C.

7. CONCLUSIONS

This investigation presents the performance analysis, environmental impact analysis and flammability analysis of the new zeotropic refrigerant R457B and its blends in a vapor compression refrigeration cycle. The conclusions drawn from this study are presented below.

- R457B (R32/1234yf/152a wt% of 35.0/55.0/10.0) increased the volumetric refrigeration capacity by 32.7%, while RGTB4 (R32/1234yf/152a wt% of 3.0/35.0/62.0) reduced it by 2.9%. In this sense, a higher percentage of R32 provides higher VRC.

- As the weight percentage of R32 or R152a increases, the discharge temperature rises, as seen in the refrigerants R457B (R32/1234yf/152a wt% of 35.0/55.0/10.0) and RGTB3 (R32/1234yf/152a wt% of 5.0/35.0/60.0). With the reduction in the composition of these refrigerants, the compressor discharge temperature decreases, a behavior shown in RGTB2 (R32/1234yf/152a wt% of 5.0/60.0/35.0).

- Although the blends analyzed reduced the mass flow rate compared to R134a, those with a higher composition of R1234yf contributed to the increase in mass flow rate, as shown in R457A (R32/1234yf/152a wt% of 18.0/70.0/12.0) and RGTB2 (R32/1234yf/152a wt% of 5.0/60.0/35.0).

- The greatest exergy destruction occurred in the compressor, followed by the expansion valve, condenser and evaporator. The refrigerants analyzed increased exergy destruction, which was expected due to the increase in compressor work.

- All the refrigerants analyzed reduced the coefficient of performance, however, RGTB4 (R32/1234yf/152a wt% of 3.0/35.0/62.0) is a blend suitable for drop-in. RGTB4 reduced COP by only 1.4% and, despite reducing VRC by 2.9%, GWP was reduced by around 13 times compared to R134a. In addition, the safety classification in terms of flammability is estimated as A2, which means medium flammability.

- By changing the evaporator temperature, it can be seen that below -8.5°C, RGTB4 provides a slightly higher COP than R134a. In this sense, the application of this blend can be more attractive in systems operating with low evaporator temperatures.

8. ACKNOWLEDGEMENTS

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