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Energy Performance Analysis of Low-GWP R32/R1234yf Refrigerant Blends for Single-Stage Heat Pump Applications

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ABSTRACT

This study presents a theoretical analysis of low-global warming potential (GWP) refrigerant blends based on R32 and R1234yf for use in single-stage heat pump systems. Six alternative refrigerant mixtures, including commercial blends (R454A, R454B, R454C), a pre-commercial formulation (DR5), and two novel proposed mixtures (Mix1 and Mix2), were investigated. The analysis was conducted by a comparative energetic performance assessment at an evaporator (+5°C) and two condenser temperature (40 and 50°C) cases. The parameters such as compressor power consumption, volumetric cooling capacity, heating capacity, and coefficient of performance for a heat pump (COP) were calculated and compared. Among the blends, R454B demonstrated the highest heating capacity and compressor power consumption, whereas Mix1 showed the lowest values for both parameters. DR5 yielded the highest volumetric cooling capacity. Although slight variations, the COP values were generally similar for the investigated blends. The results indicate that suitably selected R32/R1234yf mixtures with GWP<500 can present convenient, efficient, and environmentally favourable alternative refrigerants for future heat pump applications.

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1. Introduction

Heat pumps have become an indispensable component of sustainable buildings due to their ability to perform both heating and cooling functions with high energy efficiency. The environmental performance of heat pump systems is directly related to the thermodynamic properties and global warming potential (GWP) of the used refrigerant. The high GWP values of traditional hydrofluorocarbon (HFC)-based refrigerants have led to serious restrictions on the use of these fluids and prompted the development of low-GWP alternative refrigerant blends. In this context, new-generation refrigerants such as R32 and R1234yf have gained significant recognition in the investigations as binary or multi-component mixtures. R32 stands out for its high cooling capacity and relatively low-GWP value (~675), while R1234yf offers a major advantage in terms of reducing environmental impacts due to its extremely low-GWP (<1). However, the different thermophysical and flammability properties of both fluids make their use as mixtures more appealing than direct use.

Recent studies have shown that a new zeotropic mixture created by blending R32 and R1234yf in specific proportions can provide high energy efficiency and offer environmentally compliant alternatives. Factors such as system design, cycle performance, pressure level and safety requirements in heat pump applications play a decisive role in refrigerant selection. An increase in the amount of HFO in mixtures causes an increase in the glide temperature. In a study examining the heat transfer of R1234yf/R32 and R1234ze(E)/R32 binary mixtures, the R1234ze(E)/R32 mixture (80%/20%), which has the highest glide temperature, exhibited the lowest heat transfer coefficient [1].

The heat pump system developed using R1234yf, R32 and mixtures of the two was experimentally evaluated in terms of heating performance at low ambient temperatures. R1234yf was able to operate at evaporation temperatures as low as −25°C. The R1234yf/R32 mixture was able to operate at an evaporation temperature of −20°C and achieved the highest coefficient of performance (COP) value. The gas-injected R1234yf/R32 system provided a significant increase of 16–20% in heating capacity and 13–16% in COP compared to the non-gas-injected system [2].

The feasibility of using CO_2-based zeotropic mixtures has been investigated to improve the performance of heat pump systems that provide both residential heating and domestic hot water in extremely cold climates between -25°C and 5°C [3]. New mixtures have been created by taking advantage of the environmentally friendly and flame-retardant properties of CO_2, and the thermal efficiency contributions of R32, R1234yf and R290. The blend of R32 (90%)/CO_2 (10%) has provided the maximum COP value. The performance of a heat pump water heater using a refrigerant with low global warming potential was evaluated theoretically and experimentally under different climatic conditions [4]. The difference between simulations and experimental results is below 3%. The difference between simulation and experimental results is less than 3%. The system achieved a maximum COP value of 5.4 under tropical climate conditions. The performance of low-GWP refrigerants in vapour compression cooling and heating systems has been experimentally compared [5]. In heating mode, R513A, R516A and R1234yf were compared for evaporation temperatures of 7.5, 15 and, 22.5°C and condensation temperatures of 55°C–75°C (in 5°C increments). R513A offers an average of 3% higher heating capacity, while R516A has shown the lowest heating performance. R513A has demonstrated COP values close to R134a, especially at high evaporation temperatures.

The use of heat pumps with renewable energy sources reduces environmental impact. A comparison was performed between R410A and environmentally friendly alternative refrigerants by evaluating the life cycle climate performance (LCCP) of heat pumps [6]. The assessment covered the entire life cycle from production to disposal and carbon emissions. R32, R290, R452B and R466A have shown a significantly lower environmental impact than R410A in terms of LCCP. In countries with low emission factors, using R290 as an alternative to R410A, for example, can reduce the LCCP value by 87.8%. In order to further reduce the LCCP in the future, integrated solutions with renewable energy sources should be considered. The results are given for three binary refrigerant mixtures of R1234yf with R32, R125, and R134a [7]. The vapor–liquid equilibria properties were measured at mass fractions of R1234yf from 25% to 80% and the temperature range was 273 K – 333 K at 10 K intervals for each binary refrigerant mixture. The highest temperature glide was developed for R32/R1234yf mixture. R134a/R1234yf indicated an azeotropic property around 50/50 by weight percentage. In particular, azeotropic behaviour and temperature glide have been noted to be crucial in system design and performance prediction.

Based on tests in a heat pump, R32 and L41a were identified as good low-global warming potential (GWP) replacements for the high-GWP refrigerant R410A [8]. A simulation model was validated, showing its predictions for R32's performance was within 5% of the actual measurements. The behaviour of various fluids was assessed, concentrating on potential low GWP replacement fluids for R134a [9]. R152a and R245fa, which is highly toxic, demonstrated a higher COP than R134a, but R152a required greater compressor work. In contrast, the R1234 fluid family, particularly R1234ze, presented similar thermal performance and high exergetic efficiency. Thermodynamic analysis of 4 kW air conditioning systems was implemented to assess vapor compression heat pump system performance using R1234ze and R1234yf as alternatives to R410A [10]. For a 4-kW heat pump system, the ideal operating conditions were determined as evaporation and condensation temperatures of 20°C and 43°C, respectively. The low-GWP refrigerant R1234ze was found to be a promising alternative to R410A, performing comparably or even better.

The life cycle climate performance (LCCP) evaluation of various low-GWP refrigerants (the blends mixed with low-GWP refrigerants (HFC32/HF01234ze(E) and HFC32/ HF01234yf) was reported for R410A replacement on domestic heat pumps [11]. The binary blend of HFC32/HF01234ze(E) with a GWP of 300 exhibited the best overall environmental performance, having the lowest LCCP. It was suggested that the studied low-GWP refrigerants would become more competitive than R410A when CO_2 emission from energy generations can be diminished using the renewable energy. Another research identified 34 low-GWP refrigerant blends as potential replacements for R410A, all with a global warming potential below 150 and mild flammability [12]. Four of these mixtures (R32/R1123/R161/R13I1, R1123/R161/R13I1, R1123/R152a/R13I1 and R1123/R1234ze(E)/R13I1) were found to have a vapor pressure nearly identical to R410A, making them particularly promising candidates. While most blends demonstrated a slight decrease in COP, they met all the significant screening criteria for performance and environmental impact. Furthermore, a new non-flammable mixture called RGT2 has been developed as a more environmentally friendly alternative to R134a [13]. Its thermodynamic properties and cooling capacity were very close to those of R134a a while its COP was slightly lower. RGT2 was suggested to be an applicable substitute for R134a in heat pump systems due to its lower GWP and similar performance.

The low-GWP refrigerants (R290, R600a, R436A, R1270, R1234yf) were experimentally tested in a heat pump [14]. Using an internal heat exchanger (IHX) cycle improved efficiency for all refrigerants. The zeotropic mixture R436A showed the highest efficiency improvement using IHX (up to 27.5%), nevertheless R1270 achieved the highest efficiency overall. In a review study, 17 low-GWP refrigerants were analysed providing application guidelines for their use in vapor compression heat pumps [15]. The several low-GWP refrigerants as alternatives for to R410A were compared in a heat pump's indoor unit [16]. It was found that R32, R466A, and R454B perform similarly, while R454C and R455A show significantly reduced heat transfer. The performance of R454C and R455A could be improved with circuitry optimization to enhance their heat transfer efficiency. In a recent study, a low-GWP mixture of R1234yf/R600a was tested in a heat pump as a replacement for high-GWP R134a [17]. The mixture demonstrated a lower pressure ratio, higher mass flow rate, and favourable power consumption compared to R134a. Although its COP was slightly lower, the results indicated the studied mixture was a proper and sustainable alternative for residential heat pumps with proper optimization.

Schultz *et al*. [18] reported the performance of R454B, R454C and similar R32/R1234yf blends in a heat pump unit. Oruç and Devecioğlu [19] discussed the experimental thermodynamic performance of HFC/HFO blends R454A and R454C. Zheng *et al*. [20] compared the performance of R32/R1234yf blends using thermodynamic modeling. Ashour *et al*. [21] performed a comparative analysis of multiple low GWP fluids. Li *et al*. [22] aimed to improve energy efficiency by considering the simultaneous optimization of R32/HFO blends in terms of both refrigerant composition and heat exchanger configuration. This approach provided similar multivariate optimization strategies for R32/R1234yf blends. Halon *et al*. [23] systematically compared binary and ternary low GWP blends.

This study theoretically investigates the energy performance and environmental impacts of alternative refrigerants obtained by mixing R32 and R1234yf in different ratios for heat pump systems. The aim is to determine the optimum mixture ratios by evaluating the thermodynamic performance, COP values, and potential application advantages of the mixtures. Thus, a scientific basis can be provided for low-GWP and high-efficiency refrigerant blends in heat pump applications.

2. Materials and Methods

2.1. The Investigated Refrigerants

The study examined certain mixtures of R1234yf (HFO) and R32 (HFC) that could be used in heat pumps. Some of the refrigerants examined are commercially available (R454A, R454B, R454C) while one has not yet been assigned an R code (DR5) and the other two (Mix1, Mix2) were proposed in the present study. The examined refrigerants were selected and composed to have a GWP value which is less than 500. This enables the evaluation of suitable alternative refrigerants for heat pumps in accordance with EU criteria.

The compositions, GWP values, ASHRAE classifications, and mass fractions of the alternative refrigerants are presented in Table **1**. All the investigated refrigerants in this study are mildly flammable (A2L). Some thermodynamic and transport properties of the studied refrigerants are determined via REFPROP 10.0 software [24] and the results are given in Table **2**. These properties can be used to predict how refrigerants behave. The boiling points of all refrigerants in Table **2** are similar. The refrigerants with high critical temperatures are expected to have less compressor power consumption. A blend with low liquid density requires less refrigerant charge in the system. A high heat transfer coefficient means more heat transfer which leads to the requirement of a smaller surface area for heat exchanger such as evaporator and condenser.

Table 1: Some information on the studied refrigerants

Refrigerants	Composition	Mass %	GWP	Safety Class (ASHRAE)
R454A	R32/R1234yf	35/65	239	A2L
R454B	R32/R1234yf	68.9/31.1	466	A2L
R454C	R32/R1234yf	21.5/78.5	146	A2L
DR5	R32/R1234yf/	72.5/27.5	462	A2L
Mix1	R32/R1234yf	45/55	306	A2L
Mix2	R32/R1234yf	60/40	407	A2L

Table 2: Thermophysical properties of the examined refrigerants

Refrigerants	R454A	R454B	R454C	DR5	Mix1	Mix2
Boiling point at 1 atm (°C)	–47.8	–50.5	–45.5	–50.67	–48.9	–49.9
Critical temperature (°C)	78.9	78.1	82.4	78	79.9	78.5
Critical pressure (kPa)	4627	5267	4319	5330	4826	5106
Liquid density (kg m^{-3})	1020.9	985	1042.4	981.6	1008	992
Vapor density (kg m^{-3})	48.1	3.565	44.5	50.5	49.9	50.9
C_p liquid (kJ $kg^{-1}K^{-1}$)	1.6	1.790	1.539	1.816	1.6785	1.756
C_p vapor (kJ $kg^{-1}K^{-1}$)	1.2	0.865	1.135	1.455	1.278	1.378
k liquid (mW m^{-1} K^{-1})	83.8	105	75.6	107.8	90	99.6
k vapor (mW m^{-1} K^{-1})	14.6	13	14.4	15	14.7	15
Liquid viscosity (µPa s)	122.2	115	129.4	114.3	118.8	115.7
Vapor viscosity (µPa s)	12.3	13	12.1	12.8	11	12.7

According to ASHRAE Standard 34 [25], A2L refrigerants are classified as low-toxicity (A) working fluids with low flammability characteristics (2L), defined by a low flame propagation velocity (≤10 cm/s). In A2L-based systems, the flammability risk is primarily associated not with the intrinsic properties of the refrigerant itself, but rather with system design features and operating conditions. Scenarios such as sudden refrigerant leakage in confined spaces, insufficient ventilation, and high refrigerant charge levels may significantly increase the associated risks. The level of risk is directly proportional to the refrigerant mass per unit volume within the occupied space. Potential ignition sources include electrical arcing, static electricity discharge, and high-temperature surfaces exceeding approximately 700°C. However, due to the relatively high minimum ignition energy required for A2L refrigerants, the overall flammability risk is considerably lower when compared to A3-class refrigerants.

According to European Committee for Standardization [26], the use of A2L refrigerants in residential split-type air conditioning and heat pump applications is explicitly addressed through defined requirements related to refrigerant charge limits, ventilation provisions, leak detection systems, and additional protective measures. Appropriate detection and control strategies, including the use of A2L-compatible gas sensors, automatic compressor shutdown, and forced ventilation activation upon leak detection, are essential safety measures.

From a heat pump application perspective, refrigerant charge quantities are generally comparable to those used in split air conditioning systems. Accordingly, it is clearly demonstrated that, when appropriate system design principles and full compliance with applicable safety standards are ensured, A2L refrigerants can be safely implemented in both residential and commercial heat pump applications. Furthermore, through proper design and strict adherence to relevant standards, the associated safety risk level can be reduced to a level comparable to that of A1-class refrigerants.

2.2. Theoretical Analysis

The single stage cycle heat pump, which is schematically depicted in Fig. (**1**), is selected and modelled in this study.

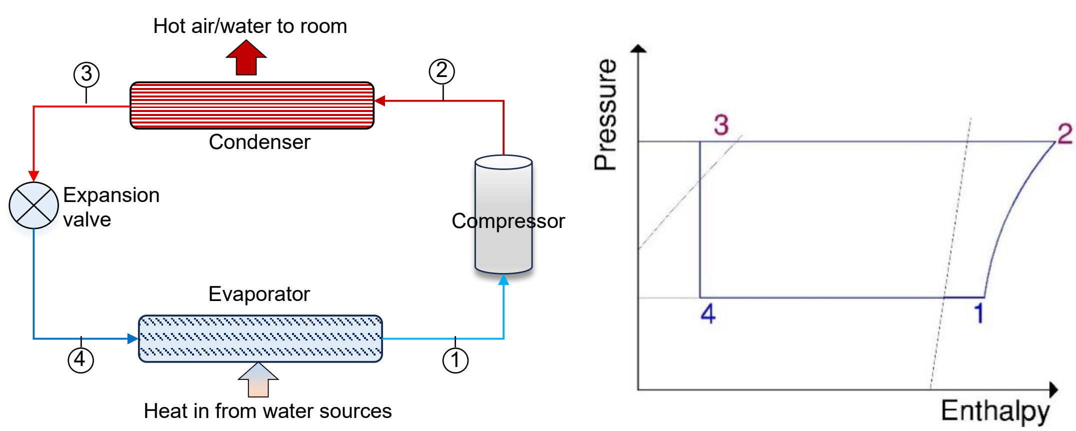

Figure 1: The schematic demonstration for investigated heat pump cycle.

The heat pump model used to compare the behaviour of refrigerants consists of a compressor, condenser, evaporator and expansion valve. The condenser and evaporator temperatures used in the model are given in Table **3**. The superheat and sub-cooling values are accepted as 3 K and 5 K, respectively for the analysis. Both isentropic efficiency and volumetric efficiency of the compressor are assumed to be 100%. Furthermore, the pressure losses through condenser and evaporator are eliminated in the theoretical analysis. The kinetic and potential energy changes are also neglected.

The process through the expansion valve is considered to be isenthalpic. The evaluations related to the energetic parameters of the system are conducted according to the thermodynamic properties of refrigerants determined using REFPROP 10.0 [24].

Table 3: The assumed values of the system variables for the analysis

Evaporator temperature, T_e (°C)	+5
Condenser temperature, T_c (°C)	40, 50
Superheat (K)	3
Sub-cooling (K)	5
Isentropic efficiency, η_i (%)	100
Volumetric efficiency (%)	100

The refrigerant mass flow rate in the system ($\dot{m}$) is computed in kg/s as

$$\dot{m} = \frac{\dot{Q}_e}{(h_1 - h_4)} \tag{1}$$

where $\dot{Q}_e$ is cooling capacity through evaporator in kW while h_1 and h_4 are enthalpy values in kJ/kg at exit and inlet of evaporator, respectively. The power consumption of the compressor ($\dot{W}_{\mathrm{el}}$) is calculated in kW as

$$\dot{W}_{\mathrm{el}} = \frac{\dot{m}(h_2' - h_1)}{\eta_i} \tag{2}$$

where h_2' is the enthalpy for isentropic process at compressor exit kJ/kg. Hence, the heating capacity of system ($\dot{Q}_h$) can be found as

$$\dot{Q}_h = \dot{Q}_e + \dot{W}_{\mathrm{el}} \tag{3}$$

The coefficient of performance (COP) for the heat pump system is calculated subsequently as

$$\mathrm{COP} = \frac{\dot{Q}_h}{\dot{W}_{\mathrm{el}}} \tag{4}$$

The volumetric cooling capacity (VCC) of the studied cases is found in kJ/m^3 as [27]

$$\mathrm{VCC} = \frac{(h_{\mathrm{v}\_T_\mathrm{e}} - h_{\mathrm{f}\_T_\mathrm{c}})}{\vartheta_{\mathrm{v}\_T_\mathrm{e}}} \tag{5}$$

where $h_{v\_T_\mathrm{e}}$ is the enthalpy of saturated vapor at evaporation temperature in kJ/kg, $h_{f\_T_\mathrm{c}}$ is the enthalpy of saturated fluid at condenser temperature in kJ/kg, and $\vartheta_{\mathrm{v}\_T_\mathrm{e}}$ is the specific volume of saturated vapor at evaporation temperature in m^3/kg.

3. Results and Discussions

The energetic analysis was carried out considering the expressions given in Eqs. (1-5). Firstly, the mass flow rate of refrigerants ($\dot{m}$) is computed via Eq. (1) for the covered situations and the results are indicated in Fig. (**2**). Since the evaporator temperature (T_e) is constant as 5°C in the study, the amounts of $\dot{m}$ are also not changing with condenser temperature (T_c) and they alter only depending on refrigerant type. It is seen that the highest and the smallest $\dot{m}$ occur for R454B and Mix1 cases with 45.2 g/s and 22.5 g/s, respectively. Also, R454B is followed by R454A and R454C having 41.8 g/s and 38.8 g/s, respectively while DR5 and Mix2 display the same $\dot{m}$ with 23.3 g/s.

The variation of VCC (i.e., computed by Eq. 5) with T_c is plotted for T_e = 5°C in Fig. (**3**). The VCC values are reduced about by 12% as T_c increases from 40 to 50°C for the refrigerants. Additionally, the refrigerant with higher critical pressure has also greater VCC value. Accordingly, the highest and the lowest VCC cases are found to emerge for DR5 and R454C, respectively, such that VCC of DR5 blend is bigger about by 2%, 9%, 25%, 39%, and 65% compared to R454B, Mix2, Mix1, R454A, and R454C, respectively for T_c = 40°C.

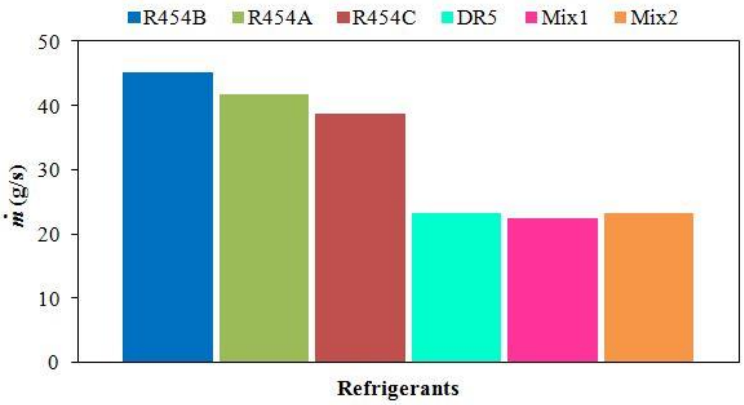

Figure 2: The distribution of mass flow rate for the investigated refrigerants.

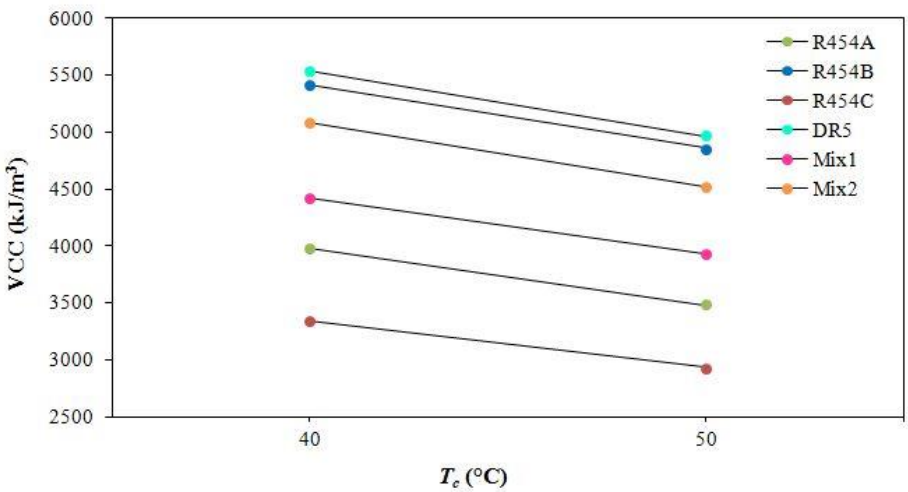

Figure 3: The variation of VCC with T_c for the studied refrigerants at T_e = 5°C.

It is aimed in heat pumps to deliver a enough amount of heating capacity ($\dot{Q}_h$) which is the summation of cooling capacity through evaporator and compressor power consumption (Eq. 3). The distribution of $\dot{Q}_h$ for the covered cases is plotted in Fig. (**4**). Evidently, $\dot{Q}_h$ enhances as T_c becomes lower for all refrigerants, for instance $\dot{Q}_h$ values are 7.4 and 6.9 kW at T_c values of 40 and 50°C, respectively for R454A. Moreover, the type of mixture directly affects the behaviour observed in Fig. (**4**) such that R454B has the greatest amount of $\dot{Q}_h$ as 10.1 kW while Mix1 gives the smallest value of 4.3 kW at T_c =40°C. In terms of the variation of $\dot{Q}_h$, R454B is followed by R454A, R454C, DR5, Mix2 and Mix1 whatever T_c is.

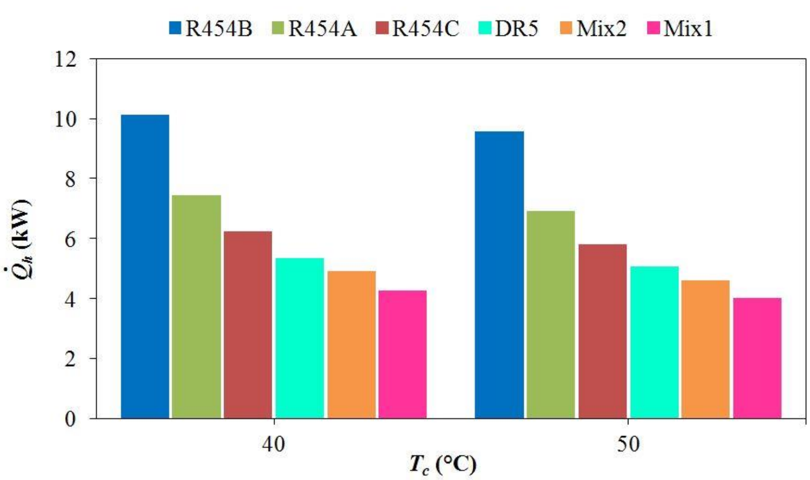

Figure 4: The variation of heating capacity with condenser temperature.

The dependence of compressor power consumption ($\dot{W}_{\text{el}}$) on T_c for the investigated refrigerants is demonstrated in Fig. (**5**). First of all, $\dot{W}_{\text{el}}$ enhances as T_c has the greater value, for example, it is augmented by 25% approximately when T_c increases from 40 to 50°C using R454C. In addition, the highest $\dot{W}_{\text{el}}$ occurs due to utilization of R454B. Besides, it can be evaluated for T_c =40°C that compared to R454B, $\dot{W}_{\text{el}}$ is lower about by 26%, 38%, 47%, 51%, and 57% using R454A, R454C, DR5, Mix2, and Mix1, respectively.

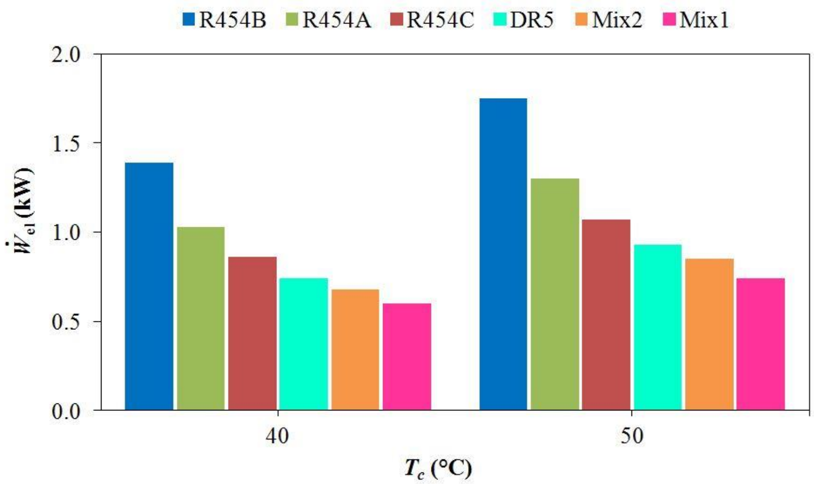

Figure 5: The variation of compressor's power consumption with condenser temperature.

The variation of coefficient of performance for the heat pump (COP) depending on investigated parameters is shown in Fig. (**6**). It is clear that COP is lower for higher T_c case for all mixtures, for instance COP is reduced about by 25% as a result of increasing T_c from 40 to 50°C in the case of R454B. Although the COP of R454B is slightly greater compared to the remaining five refrigerants for a given T_c, the order of magnitude for coefficient of performance values can be considered to be similar such that COP of Mix1 is around 7.2 and it is 7.3 approximately for R454A, R454B, R454C, DR5 and Mix2 at T_c = 40°C. Similarly, the COP values alters mildly as 5.3 to 5.5 depending on type of refrigerant at T_c = 50°C. Although the lower $\dot{Q}_h$ values of the proposed blends (Mix1 and Mix2) as seen in Fig. (**4**), their COP values are comparable and remarkable.

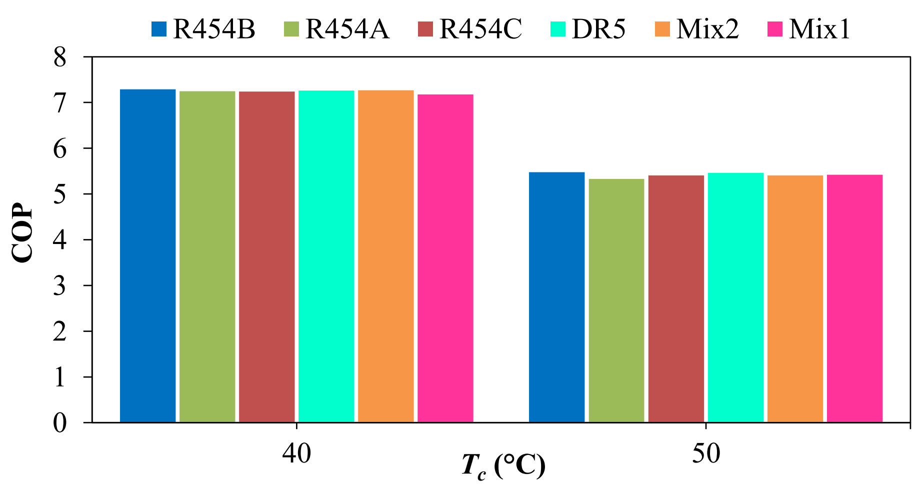

Figure 6: The variation of COP with condenser temperature for the mixtures.

4. Conclusions

This study presented a comprehensive theoretical assessment of six low-GWP refrigerant blends comprising R32 and R1234yf for single-stage heat pump applications. The evaluated mixtures were R454A, R454B, R454C, DR5 as well as two novel proposed formulations (Mix1 and Mix2). The thermodynamic performance of each blend was analysed at a constant evaporator temperature of 5°C and two condenser temperatures of 40°C and 50°C.

R454B presented the highest heating capacity and compressor power consumption, while Mix1 showed the lowest values for both parameters. DR5 emerged as the most effective in terms of volumetric cooling capacity. Although the heating capacity and power consumption changed significantly for the studied mixtures, the COP values remained almost similar for a given case of T_c.

The proposed refrigerant mixtures exhibit pressure levels and safety classifications comparable to those of the R454 series; therefore, they demonstrate strong compatibility with existing R410A/R454B-based systems and can potentially be implemented with only small system modifications.

It can be suggested that carefully prepared R32/R1234yf mixtures with GWP <500 could serve as efficient and environmentally suitable alternatives to traditional HFC refrigerants in heat pump systems. Among the evaluated refrigerant blends, R454B emerges as the most favourable in terms of heating capacity. From an environmental perspective, R454C is the best option with the lowest GWP value of 146. On the other hand, Mix1, one of the novel blends proposed in this study, provides a suitable balance among the alternatives. As long as the required heating capacity is satisfied, it has a competitive COP and a low GWP value of 306, making it a sustainable candidate for heat pump applications where both performance and environmental impact must be considered.

Conflict of 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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