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REESEARCH PAPER

Thermodynamic performance evaluation of VCRS systems using HFO+HFC Blended refrigerants for replacing high-GWP eco-friendly HFC and HCFC refrigerants

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Abstract

Hydrofluorocarbons are the most widely used refrigerants worldwide. However, the HFCs will soon be phased out entirely due to environmental concerns. The high global warming potential (GWP) of HFCs is the main reason for their phase-out. Therefore, scientists, engineers in the refrigeration sector are looking for a suitable, environmentally friendly replacement of high GWP refrigerants for replacing high GWP of mostly HFCs in the VCR systems. In this paper, the use of HFOs, HCFOs, and HFC+HFO blended refrigerants were suggested. Hydrofluoro-olefins (HFOs), are a new family of eco-friendly refrigerants that have just surfaced. The thermodynamic performance of in simple vapour compression refrigeration systems have been evaluated using HCFO-1224yd(Z), HCFC-1233zd(E) and HFO-1336mzz(Z) for replacing HCFC-123and HFC-245fa have been examined in detail. Also Effect of other HFOs (R1225ye(Z), R1243zf, R1234ze(E) & R1234yf) on thermodynamic performances for replacing HFC-134a & HFC-404a were compared. Blended HFO refrigerants (R450A, R513A, R515A, R454b, R454c, R448a, R449A) for replacing HFC refrigerants investigated.

1. Introduction

The latest developments in this technology reduce the energy consumption of cooling systems, hence minimizing their direct environmental impact. Additionally, it aims to support researchers who are interested in lessening the environmental impact of building cooling systems. It also provides suitable replacements for the current refrigerants to reduce the direct environmental impact of cooling systems. Passive techniques can also be used to reduce the cooling burden or, in some cases, take the place of mechanical systems. First-generation refrigerants, known as chlorofluorocarbons, have been phased out and second-generation refrigerants, known as hydrochlorofluorocarbons are being phased out due to the harm they have done to the ozone layer. Hydrofluorocarbons, a third-generation refrigerant, are also being phased out because of their high potential for global warming. Hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs) were developed as replacements for the three generations of refrigerants. Due to their safety and environmental friendliness, they have been drawing more and more attention from researchers. According to the National Academy of Engineering's list of the top 20 engineering achievements of the 20th century, air conditioning and refrigeration were crucial to both industrial production and people's daily lives. The first artificial refrigeration techniques were developed by William Cullen in 1755 when he created a small refrigerating machine using diethyl ether. In 1835, Jacob Perkins, dubbed "The Father of the Refrigerator," received the first patent for the vapour-compression refrigeration cycle under the title "Apparatus and means for producing ice, and in cooling fluids." Natural substances like carbon dioxide (CO_2),

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ammonia (NH_3), sulfur dioxide (SO_2), isobutane (HC-600a), and propane (HC-290) were the most popular refrigerants at the time. These refrigerants, however, were either flammable, toxic, or both. Additionally, some refrigerants were extremely unstable and corrosive [1].

1.1 Drawbacks using natural refrigerants

The most promising natural refrigerants are carbon dioxide and water, which are the safest and most efficient ways to lessen the environmental issues associated with the vapour compression cycle. Water is a very safe and efficient refrigerant that might solve most environmental problems associated with refrigerants. Further research is required to resolve the technical problems with using water as a refrigerant. The recommended methods for using water as a refrigerant include direct expansion and condensing techniques, as well as promoting industry cooperation to reduce the cost of water compressors. A cascade refrigeration cycle and cycle changes like an expander or two-phase ejector could improve the refrigeration cycle's performance.

First-generation refrigerants, known as chlorofluorocarbons have been phased out and second-generation refrigerants known as hydrochlorofluorocarbons are being phased out due to the harm they have caused to the ozone layer. Because of their high global warming potential (GWP), third-generation refrigerants called hydrofluorocarbons are also being phased out. Hydrofluoroolefins and hydrochlorofluoroolefins were developed in labs as replacements for the three generations of refrigerants. Because they are safe and eco-friendly, they have been employed in vapor compression cycles. The many facets of hydrofluoroolefin and hydrochlorofluoroolefin refrigerants are examined and talked about. HFO-1234yf and HFO-1234ze (E) continue to be the most researched hydrofluoroolefins (HFOs). Further consideration should be given to HFO-1336mzz(Z) and HCFOs (R1233zd(E) & R1224yd(Z), as they could be an appropriate substitute for HFC-123 [Mishra2025].

Hydrofluoroolefin (HFO) blends offer a sustainable, low-global-warming-potential (GWP) alternative to HFCs and CFCs in Vapor Compression Refrigeration Systems (VCRS). While pure HFOs like R1234yf and R1234ze(E) sometimes exhibit a slightly lower Coefficient of Performance (COP) than R134a,

The increasing concerns on environmental sustainability and the resultant strict regulations, such as EU Regulation 517/2014 and the Kigali Amendment to the Montreal Protocol, have increased interest in low-global warming potential (GWP) refrigerants for vapor compression refrigeration (VCR) systems. This work studies the efficiency of low GWP refrigerants in a VCR system used for water cooling. More specifically, it compares the performance of the hydrocarbons R290 (propane) and R1270 (propylene), the hydrofluoroolefin R1234yf, and the HFO-HFC mixture R454C with the conventional refrigerants R134a and R404A. Based on theoretical modeling combined with experimental investigation carried out in controlled conditions at a condenser temperature of 45 °C, evaporator temperature of 0 °C, and ambient temperature of 30 °C, key performance parameters, including energy consumption, refrigeration effect, coefficient of performance (COP), and pressure ratio, are analyzed. The results show that R290 has the best performance, with a COP of 3.0, which is 3.2 %, 6.8 %, and 25.2 % higher than that of R1270, R1234yf, and R454C, respectively. Moreover, R290 has a considerable energy saving compared with R404A [2,3].

Experimental numerical investigation on one stage vapour compression refrigeration system for studied refrigerants (R22, R134a, R717, R507a, R404a) in terms of COP, compressor work, exergy efficiency and refrigeration effect. Effect of subcooling, superheating and compression ratio are also studied on the same system using the considered refrigerants and a system optimization is also presented when working with specific refrigerant in the vapour compression [4, 5].

The use of hydrocarbons and mixture compressor shows much higher exergy destruction as compared to rest of the components in the vapour compression refrigeration system and this exergy destruction can be minimized by using of nanofluid and nanolubricants in compressor. The analyzes also showed the blend with a negligible impact on the greenhouse effect and at the same time good thermodynamic properties, which could be used as a replacement for R404A or R507A in low-temperature systems. Both of the proposed mixtures have disadvantages compared to currently used refrigerants. Although the R32–R41 achieves high volumetric cooling capacity, it is also characterized by high evaporating and condensing pressures and high discharge temperatures, which will result in higher thermal and force loads of the compressor working elements and may lead to their shorter life span. On the other hand, the R161–R41–R1234ze(E) mixture, despite the high coefficient of performance, shows nearly ten times higher temperature glide than R404A [6].

2. Vapour compression refrigeration cycle

The objectives of a refrigeration cycle are heat rejection and absorption. The refrigeration cycle, sometimes referred to as a heat pump cycle, directs heat away to cool. This is accomplished by changing the operating refrigerant's pressure through a cycle of compression and expansion (air, water, synthetic refrigerants, etc.). Vapour compression refrigeration systems significantly contribute to global warming both directly and indirectly. Furthermore, no other technology will be able to take the place of the vapour compression cycle anytime soon. Therefore, it is crucial to lessen the adverse environmental effects of the vapour compression cycle.

The following factors should be taken into account to enhance vapour compression refrigeration systems' thermodynamic performance:

- The refrigeration cycle COP can be raised by increasing superheating and subcooling or recovering expansion losses.
- Suction line heat exchangers, mechanical sub-cooling, and thermo-electric sub-cooling are additional methods to boost sub-cooling and super-heating.
- The ideal sub-cooling or super-heating method depends on the application and is strongly related to the refrigerant's properties.

- A cascade refrigeration cycle and cycle modifications like an expander or two-phase ejector could improve the refrigeration cycle's performance.
- The recommended methods for using water as a refrigerant include direct expansion and condensing techniques, as well as promoting industrial cooperation to reduce the cost of water compressors.

However, they mainly depend on the thermophysical properties of the refrigerant, so choosing the optimal technique requires careful research [7]. Experimentally comparative analysis of R32, R152a and R134a refrigerants in vapour compression refrigerator and concluded that R32 shows lowest performance whereas R134a and R152a showing nearly same performance but best performance was obtained of system using R152a [8]**.** Exergy analysis of domestic vapour compression refrigeration system with R12 and R413A was carried out and concluded that performance in terms of power consumption, irreversibility and exergy efficiency of R413A is better than R12, so R12 can be replaced with R413A in domestic vapour compression refrigeration system [9]. The replacement of R12 with R410a through experimental investigation of medium temperature vapour compression refrigeration cycles. In terms of thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, R410a gives best performance among R404a and R290a [10]. Experimental and simulation investigation of the performance and characteristics of different refrigerants and blends of refrigerants is carried out by authors, to replace the existing refrigerant R134a for a vapour compression refrigeration system. The performance of VCRS systems was improved by several researchers by introducing the concept of mixing the family of refrigerants with low GWP in the working circuit and found that the performance results of different refrigerants and blends of refrigerants that can replace the R134a and considered to cover the mechanism and possible combination of different blends of refrigerants to improve the effectiveness as well as efficiency of the refrigeration system. Detailed analysis of different parameters of heat transfer and predictions of low-GWP refrigerants, including the HFO (hydro fluoro-olefin) class and the HC (hydrocarbon) class through energy and exergy analysis of commercial refrigerants such as R134a is performed [11]. Based on the literature it was observed that researchers have gone through detailed first law analysis in terms of coefficient of performance and second law analysis in term of exergetic efficiency of simple vapour compression refrigeration system with single evaporator. Researchers did not go through the irreversibility analysis (second law analysis) of followings:

(i)Simple VCR system with, flash intercooler, flash chamber, water intercooler, liquid sub-cooler and stages in compression(double stage and triple stage) (ii)multiple evaporators systems with multi-stage expansion and compound compression in vapour compression refrigeration systems (iii)detailed analysis of vapour compression refrigeration systems using thirteen ecofriendly refrigerants improve thermal performance of vapour compression refrigeration systems both multiple evaporator system by using liquid vapour heat exchanger for improving[12] . First law efficiency (COP), second law efficiency (Exergetic efficiency) and Reduction of system defect in components of system in terms of exergy destruction ratio which results into reduction of work input and found that (iv)Flash chamber responsible for lowest exergy destruction for all HFO refrigerants taken under consideration [13].

2.1 HFO Blends used in VCR Systems

In medium and high-temperature commercial refrigeration and HVAC systems, R450A, an eco-friendly, non-flammable refrigerant (ASHRAE A1), is intended to replace R134a. While retaining comparable cooling performance and energy efficiency, it offers an approximately 60% reduction in Global Warming Potential (GWP) when compared to R134a. Since R450A and R134a have comparable operating pressures and characteristics, replacing R134a with R450A is usually simple. R450A is a good "drop-in" or "retrofit" alternative. In commercial refrigeration systems and chillers, R-513A is mostly used to replace R-134a. It is a nearly drop-in replacement that requires little to no system adjustments and greatly reduces environmental effect. Because R-513A has a Global Warming Potential (GWP) of between 573 and 631, which is more than a 50% decrease from R-134a's GWP of roughly 1430, it has a lesser environmental impact. This refrigerant is totally ozone-friendly, non-flammable, and nearly perfectly matches the cooling capacity and energy efficiency of R-134a. An azeotropic hydrofluoroolefin (HFO) mix called R-515A was created as a low-GWP (402) replacement for R134a. Replacing legacy fluids like R134a in existing units frequently necessitates special retrofitting adjustments because R-515A operates with lower discharge temperatures and pressures.

Because R-454B is an A2L slightly flammable gas, replacing a refrigerant system requires caution. R-454B cannot be "pumped down" into the condenser for the R-410A system to R-454B due to safety regulations. A complete system replacement is frequently necessary because compressors, valves, and electrical safeguards are not made for A2L refrigerants. In commercial refrigeration, R454C, a mildly flammable (A2L) HFO blend, takes the place of R404A and R22. It is a long-term, sustainable option with a Global Warming Potential (GWP) of 148. because it uses varying pressures and a temperature glide.

In commercial and transport refrigeration, R-452A is frequently used in place of R-404A and R-507. R448A, also called Solstice N40, is often used to replace high-GWP refrigerants like R404A and R507A since it is an almost drop-in replacement with comparable pressures and mass flow rates, so you typically don't need to replace the expansion valve. Similar operating pressures, comparable capacities, and frequently a 5–15% reduction in energy consumption characterize an HFO blend with a significantly lower Global Warming Potential (GWP). Global phase-out restrictions pertaining to medium-to-high GWP refrigerants necessitate vigilance while replacing R-449A.

An energetic and exergetic assessment of the vapour compression refrigeration system was carried out using various HFO and HFC refrigerants to evaluate their thermodynamic performance. The analysis revealed significant differences among the refrigerants in terms of energy utilization and irreversibility. Among the refrigerants investigated, R32 exhibited the lowest exergetic performance, indicating comparatively poor utilization of available energy. It was also observed that the condenser accounted for the largest share of exergy destruction for all HFO and HFC refrigerants, identifying it as the major source of thermodynamic irreversibility within the refrigeration system. Furthermore, compressors operating with R1233zd(E) and R1225ye(Z) experienced comparatively higher exergy destruction than those using the other HFO refrigerants, suggesting greater losses during the compression process [14].

3. Results and Discussion

The input parameters and environmental parameters (i.e., GWP and ODP) of eco-friendly low-GWP refrigerants used in vapour compression refrigeration are shown in Table 1 (a) to Table 1 (d), respectively.

Table 1(a): Input parameters of vapour compression refrigeration systems.

Input parameters	unit
Condenser temperature	50°C
Evaporator temperature	-10 °C
Isentropic Compressor Efficiency	80%
Cooling Load	10kW
Subcooling temperature	5 °C
Superheating temperature	5 °C

Table 2(b): Environmental parameters of HFO+HFC refrigerants

HFO blended ecofriendly Refrigerants (with HFO + HFC composition)	GWP	ODP	Safety Code
R450A (Solstics N13) nonflammable using 58% HFO-1234ze(E) + 42%HFC-134A Blend	547	0	A1
R513A (nonflammable using 56% HFO-1234yf + 44% HFC-134A Blend)	573-631	0	A1
R515A (nonflammable using 88% HFO-1234ze(E) + 12% HFC-227EA Blend)	402	0	A1
R454b (nonflammable using 31.1% HFO-1234yf + 68.9% HFC-32 Blend)	466	0	A1
R454c (nonflammable using 78.5% HFO-1234yf + 21.5% HFC-32 Blend)	148	0	A2L
R452A (HFO - 1234yf + HFC-32 + HFC-125	1387	0	A1
R448A (20% HFO -1234yf + 26% HFC-32 + 26%HFC-125 + 20% HFC-134A	1387	0	A1
R449A (25% HFO-1234yf + 24% HFC-32 + 25%HFC-125 + 26% HFC-134A	1397	0	A1

Table 3(c): Environmental parameters of HCFO&HFO refrigerants

Ecofriendly HCFO and HFO ecofriendly Refrigerants	GWP	ODP	Safety Code
HCFO-1224yd(Z)	0.88	0.00023	A1
HCFO-1233zd(E)	4.5	0.00033	A1
HFO-1336mzz(Z)	2	0	A1
HFO-1225ye(Z)	1	0	A1
HFO-1243zf	0.82	0	A2L
HFO-1234ze(E)	6-7	0	A2L
HFO-1234yf	4	0	A2L
HFO-1234ze(Z)	1	0	A1

Table 4(d): Environmental parameters of HFC refrigerants

Eco-friendly HFC and HCFC Refrigerants	GWP	ODP	Safety Code
R152A	124	0	A2
R245FA	858 to 1030	0	A1
R32	675	0	A1
R123	73-77	0	B1
R-507A (using 50% HFC-125 + 50% HFC-143A Blend refrigerant)	3985	0	A2L
R-404A using 44% HFC-125 + 52% HFC-143A + 4% R134a Blend refrigerant)	3922	0	A1
R-410A using 44% HFC-125 + 52% HFC-143A + 4% R134a Blend refrigerant)	2088	0	A1
R134a refrigerant	1430	0	A1
R407c	1774	0	A1

3.1 Maximum thermal performance of vapour compression refrigeration system using HFO blended refrigerants

Table 2(a) compares the thermodynamic and exergetic performance of the HFO-blended refrigerant R448A with the conventional high-GWP refrigerants R507A and R404A under identical operating conditions. The results show that R448A provides the best overall performance among the three refrigerants. The coefficient of performance (COP) of R448A is 3.064, which is higher than that of R507A (2.966) and R404A (2.973), indicating that R448A delivers the required cooling capacity with lower compressor work. Similarly, the exergy efficiency of R448A is 0.3429, compared with 0.3320 for R507A and 0.3327 for R404A, demonstrating more effective utilization of the available energy. The exergy destruction ratio is also the lowest for R448A (1.916), whereas R507A and R404A exhibit higher values of 2.012 and 2.005, respectively, indicating lower thermodynamic irreversibilities in the refrigeration cycle. Furthermore, the exergy of fuel required by R448A is 3.264 kW, which is lower than 3.372 kW for R507A and 3.364 kW for R404A, reflecting reduced energy input for achieving the same refrigeration effect. Since the exergy of the product remains constant at 1.119 kW for all refrigerants due to the identical cooling load, the superior COP, higher exergy efficiency, lower exergy destruction ratio, and reduced fuel exergy clearly demonstrate that R448A is a more energy-efficient and environmentally sustainable replacement for R507A and R404A, offering improved system performance while contributing to the reduction of global warming potential.

Table 2(a): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant (R448a) for replacing High GWP eco-friendly HFC refrigerants (R507a and R404a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%

Refrigerant	R448a	R507a	R404a
First law Efficiency (COP_{VCRS})	3.064	2.966	2.973
Exergy Efficiency	0.3429	0.332	0.3327
Exergy Destruction Ratio	1.916	2.012	2.005
Exergy of fuel (kW)	3.264	3.372	3.364
Exergy of Product (kW)	1.119	1.119	1.119

Table 2(b) presents the comparative thermal and exergetic performance of the HFO-based refrigerant R449A with the conventional refrigerants R507A and R404A under the same operating conditions. The results indicate that R449A also performs better than the conventional HFC refrigerants, although its improvement is slightly smaller than that of R448A. The COP of R449A is 2.986, which is marginally higher than 2.966 for R507A and 2.973 for R404A, indicating a slight reduction in compressor power requirement for the same cooling capacity. Likewise, the exergy efficiency of R449A reaches 0.3342, exceeding the values of 0.3320 and 0.3327 obtained for R507A and R404A, respectively, suggesting more effective utilization of available energy. The exergy destruction ratio of R449A is 1.992, which is lower than 2.012 for R507A and slightly lower than 2.009 for R404A, indicating a modest reduction in system irreversibilities. In addition, the exergy of fuel required by R449A is 3.349 kW, which is lower than 3.372 kW for R507A and slightly lower than 3.364 kW for R404A, demonstrating a reduction in energy consumption while maintaining the same refrigeration capacity. The exergy of the product remains unchanged at 1.119 kW for all refrigerants because the cooling load is fixed. Overall, the results confirm that R449A offers improved thermodynamic and exergetic performance over R507A and R404A, making it a suitable low-GWP alternative for reducing environmental impact while maintaining comparable refrigeration system efficiency.

Table 2(b): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant (R449a) for replacing High GWP eco-friendly HFC refrigerants (R507a and R404a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R449a	R507a	R404a
First law Efficiency (COP_{VCRS})	2.986	2.966	2.973
Exergy Efficiency	0.3342	0.3320	0.3327
Exergy Destruction Ratio	1.992	2.012	2.009
Exergy of fuel (kW)	3.349	3.372	3.364
Exergy of Product (kW)	1.119	1.119	1.119
Refrigerant	R449a	R507a	R404a

Table 2(c) compares the thermal and exergetic performance of the low-GWP HFO blend R450A with the conventional high-GWP refrigerant R134A under identical operating conditions. The results indicate that R450A exhibits slightly lower thermodynamic performance than R134A. The coefficient of performance (COP) of R450A is 3.344, compared with 3.492 for R134A, indicating a marginal increase in compressor work to produce the same cooling capacity. Similarly, the exergy efficiency of R450A is 0.3743, which is lower than 0.3909 for R134A, suggesting a slight reduction in the effectiveness of energy utilization. The exergy destruction ratio increases from 1.558 for R134A to 1.672 for R450A, indicating relatively higher irreversibilities within the refrigeration cycle. Furthermore, the exergy of fuel required by R450A is 2.991 kW, whereas R134A requires only 2.864 kW, confirming the higher energy input needed by R450A to achieve the same refrigeration effect. The exergy of the product remains constant at 1.119 kW for both refrigerants because the refrigeration capacity is maintained at 10 kW. Although R450A demonstrates a small reduction in thermal and exergetic performance compared with R134A, its significantly lower global warming potential makes it a promising environmentally sustainable substitute for conventional HFC refrigerants. Table 2(d) presents the comparative performance of the environmentally friendly HFO blend R513A and the conventional refrigerant R134A. The results show that R513A performs slightly below R134A in terms of energy and exergy efficiencies. The COP of R513A is 3.325, which is lower than the 3.492 achieved by R134A, indicating a marginally higher compressor power requirement. Likewise, the exergy efficiency decreases from 0.3909 for R134A to 0.3722 for R513A, reflecting a modest decline in thermodynamic effectiveness. The exergy destruction ratio of R513A is 1.687, exceeding the value of 1.558 for R134A, which signifies increased system irreversibilities. Similarly, the exergy of fuel increases from 2.864 kW for R134A to 3.008 kW for R513A, indicating that slightly more input exergy is required to produce the same refrigeration capacity. Since the exergy of the product remains unchanged at 1.119 kW, the observed differences are primarily associated with the refrigerant characteristics and compressor energy requirement. Despite its slightly lower thermal performance, R513A offers substantial environmental benefits due to its considerably lower GWP, making it a viable replacement for R134A where environmental sustainability is prioritized over marginal efficiency losses.

Table 2(c): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant (R450a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R450a	R134a
First law Efficiency (COP_{VCRS})	3.344	3.492
Exergy Efficiency	0.3743	0.3909
Exergy Destruction Ratio	1.672	1.558
Exergy of fuel (kW)	2.991	2.864
Exergy of Product (kW)	1.119	1.119

Table 2(d): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant (R513a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R513a	R134a
First law Efficiency (COP_{VCRS})	3.325	3.492
Exergy Efficiency	0.3722	0.3909
Exergy Destruction Ratio	1.687	1.558
Exergy of fuel (kW)	3.008	2.864
Exergy of Product (kW)	1.119	1.119

Table 2(e) compares the thermal and exergetic performance of the low-GWP refrigerant R515A with the conventional refrigerant R134A. Among the HFO blends investigated for replacing R134A, R515A demonstrates the closest performance to the baseline refrigerant. The COP of R515A is 3.452, which is only slightly lower than 3.492 for R134A, indicating that nearly the same refrigeration performance can be achieved with a minimal increase in compressor work. Similarly, the exergy efficiency of R515A is 0.3868, which is very close to the 0.3909 obtained with R134A, suggesting highly efficient utilization of available energy. The exergy destruction ratio increases only marginally from 1.558 for R134A to 1.588 for R515A, indicating only a slight increase in thermodynamic irreversibilities. Likewise, the exergy of fuel required by R515A is 2.897 kW, compared with 2.864 kW for R134A, representing only a small increase in the required input exergy. The exergy of the product remains constant at 1.119 kW because the refrigeration load is identical for both refrigerants. Overall, the results demonstrate that R515A provides thermal and exergetic performance very close to that of R134A while offering the significant advantage of a much lower global warming potential. Consequently, R515A emerges as the most suitable environmentally friendly replacement for R134A among the HFO blends evaluated, combining high energy efficiency with reduced environmental impact.

Table 2(e): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R515a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R515a	R134a
First law Efficiency (COP_{VCRS})	3.452	3.492
Exergy Efficiency	0.3868	0.3909
Exergy Destruction Ratio	1.588	1.558
Exergy of fuel (kW)	2.897	2.864
Exergy of Product (kW)	1.119	1.119

Table 2(e) presents the thermal and exergetic performance comparison between the low-GWP HFO blend R515A and the conventional high-GWP refrigerant R134A under identical operating conditions. The results indicate that R515A exhibits performance very close to that of R134A, making it one of the most promising environmentally friendly alternatives. The coefficient of performance (COP) of R515A is 3.452, which is only slightly lower than the 3.492 obtained with R134A, indicating that nearly the same refrigeration effect can be achieved with a marginal increase in compressor work. Similarly, the exergy efficiency of R515A is 0.3868, which is very close to the 0.3909 of R134A, demonstrating comparable utilization of the available energy. The exergy destruction ratio of R515A is 1.588, slightly higher than 1.558 for R134A, indicating only a minor increase in thermodynamic irreversibilities. Likewise, the exergy of fuel required by R515A is 2.897 kW, compared with 2.864 kW for R134A, while the exergy of the product remains constant at 1.119 kW for both refrigerants because the refrigeration capacity is maintained at 10 kW. These results confirm that although R515A experiences a negligible reduction in thermal performance compared with R134A, it offers the significant advantage of a substantially lower global warming potential, making it an excellent long-term replacement for conventional HFC refrigerants.

Table-2(f): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R454b) for replacing High GWP eco-friendly HFC refrigerants(R410a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R454b	R410a
First law Efficiency (COP_{VCRS})	3.214	3.210
Exergy Efficiency	0.3598	0.3593
Exergy Destruction Ratio	1.779	1.783
Exergy of fuel (kW)	3.111	3.115
Exergy of Product (kW)	1.119	1.119

Table 2(f) compares the performance of the HFO blend R454B with the conventional refrigerant R410A under the same operating conditions. The results demonstrate that R454B provides slightly superior thermodynamic and exergetic performance compared with R410A. The COP of R454B is 3.214, which is marginally higher than 3.210 for R410A, indicating a small improvement in refrigeration efficiency. Similarly, the exergy efficiency of R454B is 0.3598, slightly exceeding the 0.3593 obtained with R410A, reflecting marginally better utilization of the supplied energy. The exergy destruction ratio decreases from 1.783 for R410A to 1.779 for R454B, indicating a slight reduction in system irreversibilities.

Table 2(g): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R454c) for replacing High GWP eco-friendly HFC refrigerants(R404a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R454c	R404a
First law Efficiency (COP_{VCRS})	2.840	2.973
Exergy Efficiency	0.3179	0.3327
Exergy Destruction Ratio	2.146	2.009
Exergy of fuel (kW)	3.522	3.364
Exergy of Product (kW)	1.119	1.119

In addition, the exergy of fuel required by R454B is 3.111 kW, which is marginally lower than 3.115 kW for R410A, while the exergy of the product remains constant at 1.119 kW for both refrigerants. These findings indicate that R454B not only maintains the cooling performance of R410A but also provides a slight improvement in energy and exergy efficiencies while significantly reducing the global warming potential, making it a highly suitable eco-friendly replacement.

Table 2(g) presents the comparative thermal and exergetic performance of the low-GWP refrigerant R454C and the conventional refrigerant R404A. The results show that R454C exhibits slightly lower thermodynamic performance than R404A under identical operating conditions. The COP of R454C is 2.840, compared with 2.973 for R404A, indicating a higher compressor work requirement to achieve the same cooling capacity. Likewise, the exergy efficiency of R454C is 0.3179, which is lower than 0.3327 for R404A, suggesting a slight reduction in the effective utilization of available energy. The exergy destruction ratio increases from 2.009 for R404A to 2.146 for R454C, indicating relatively higher thermodynamic irreversibilities. Similarly, the exergy of fuel required by R454C is 3.522 kW, exceeding the 3.364 kW required by R404A, whereas the exergy of the product remains unchanged at 1.119 kW because the refrigeration load is constant. Although R454C demonstrates a modest reduction in energy and exergy performance compared with R404A, its considerably lower global warming potential and improved environmental compatibility make it a viable alternative for applications where environmental sustainability is prioritized over a small decrease in system efficiency.

3.2 Actual thermal performance of vapour compression refrigeration system using HFO blended refrigerants

The actual thermal and exergetic performance of the simple vapour compression refrigeration system operating at 80% isentropic compressor efficiency is presented in Tables 3(a)–3(g) for various low-GWP HFO blends as replacements for conventional high-GWP HFC refrigerants. The reduction in compressor efficiency results in lower COP and exergy efficiency and higher exergy destruction and fuel exergy for all refrigerants compared with the ideal (100% efficiency) condition. Nevertheless, the HFO blends exhibit performance comparable to or better than their conventional counterparts while offering significant environmental benefits through lower global warming potential.

Table 3(a) compares R448A with R507A and R404A. Among these refrigerants, R448A exhibits the best thermodynamic performance with a COP of 2.451, compared with 2.373 for R507A and 2.378 for R404A. Similarly, the exergy efficiency of R448A is 0.2744, which is higher than 0.2656 and 0.2662 obtained for R507A and R404A, respectively. The exergy destruction ratio is the lowest for R448A (2.645), whereas R507A and R404A show higher values of 2.765 and 2.757, indicating reduced irreversibilities. Furthermore, the exergy of fuel required by R448A is 4.080 kW, lower than 4.215 kW for R507A and 4.205 kW for R404A, while the exergy of the product remains constant at 1.119 kW for all refrigerants. These results confirm that R448A provides superior energy and exergy performance and represents an efficient low-GWP substitute for R507A and R404A.

Table 3(a): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R448a) for replacing High GWP eco-friendly HFC refrigerants (R507a and R404a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R448a	R507a	R404a
First law Efficiency (COP_{VCRS})	2.451	2.373	2.378
Exergy Efficiency	0.2744	0.2656	0.2662
Exergy Destruction Ratio	2.645	2.765	2.757
Exergy of fuel (kW)	4.08	4.215	4.205
Exergy of Product (kW)	1.119	1.119	1.119

Table 3(b): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R448a) for replacing High GWP eco-friendly HFC refrigerants (R507a and R404a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R449a	R507a	R404a
First law Efficiency (COP_{VCRS})	2.389	2.373	2.378
Exergy Efficiency	0.2674	0.2656	0.2662
Exergy Destruction Ratio	2.74	2.765	2.757
Exergy of fuel (kW)	4.186	4.215	4.205
Exergy of Product (kW)	1.119	1.119	1.119

Table 3(b) presents the performance comparison of R449A with R507A and R404A. The results indicate that R449A also performs slightly better than the conventional refrigerants, although its performance is marginally lower than that of R448A. The COP of R449A is 2.389, exceeding 2.373 for R507A and 2.378 for R404A. Likewise, the exergy efficiency of R449A is 0.2674, slightly higher than those of R507A (0.2656) and R404A (0.2662). The exergy destruction ratio decreases to 2.740 for R449A compared with 2.765 for R507A, although it remains marginally higher than 2.757 for R404A. The exergy of fuel required by R449A is 4.186 kW, which is lower than 4.215 kW for R507A and only slightly lower than 4.205 kW for R404A, whereas the exergy of the product remains unchanged at 1.119 kW. Overall, R449A provides modest improvements over conventional HFC refrigerants and serves as an environmentally friendly alternative with acceptable thermal performance.

Table 3(c): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R450a) for replacing High GWP eco-friendly HFC refrigerants (R507a and R404a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R450a	R134a
First law Efficiency (COP_{VCRS})	2.675	2.794
Exergy Efficiency	0.2994	0.3127
Exergy Destruction Ratio	2.340	2.198
Exergy of fuel (kW)	3.738	3.579
Exergy of Product (kW)	1.119	1.119

Table 3(c) compares the performance of R450A and R134A.

The results reveal that R450A exhibits slightly lower thermodynamic performance than R134A under actual operating conditions. The COP decreases from 2.794 for R134A to 2.675 for R450A, while the exergy efficiency decreases from 0.3127 to 0.2994. The exergy destruction ratio increases from 2.198 for R134A to 2.340 for R450A, indicating increased thermodynamic irreversibilities. Similarly, the exergy of fuel increases from 3.579 kW to 3.738 kW, whereas the exergy of the product remains constant at 1.119 kW. Although R450A shows a slight reduction in thermal performance, its substantially lower GWP makes it an attractive replacement for R134A.

Table 3(d): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R513a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R513a	R134a
First law Efficiency (COP_{VCRS})	2.660	2.794
Exergy Efficiency	0.2977	0.3127
Exergy Destruction Ratio	2.359	2.198
Exergy of fuel (kW)	3.760	3.579
Exergy of Product (kW)	1.119	1.119

Table 3(d) presents the comparison between R513A and R134A. The COP of R513A is 2.660, which is slightly lower than 2.794 for R134A. Likewise, the exergy efficiency decreases from 0.3127 to 0.2977, while the exergy destruction ratio increases from 2.198 to 2.359. The exergy of fuel required by R513A is 3.760 kW, slightly higher than 3.579 kW for R134A, whereas the exergy of the product remains 1.119 kW for both refrigerants. These results indicate that R513A experiences a moderate reduction in energy and exergy performance but remains a practical low-GWP alternative for replacing R134A.

Table 3(e): Effect of eco-friendly refrigerants on actual thermal performances of simple VCRS using HFO blended Refrigerant(R515a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R515a	R134a
First law Efficiency (COP_{VCRS})	2.761	2.794
Exergy Efficiency	0.3091	0.3127
Exergy Destruction Ratio	2.282	2.198
Exergy of fuel (kW)	3.621	3.579
Exergy of Product (kW)	1.119	1.119

Table 3(e) compares R515A with R134A under the same operating conditions. Among the HFO blends evaluated for replacing R134A, R515A provides the closest performance to the baseline refrigerant. The COP of R515A is 2.761, only slightly lower than 2.794 for R134A, while the exergy efficiency reaches 0.3091, compared with 0.3127 for R134A. The exergy destruction ratio of R515A is 2.282, which is only marginally higher than 2.198 for R134A, and the exergy of fuel increases only slightly from 3.579 kW to 3.621 kW. Since the exergy of the product remains constant at 1.119 kW, the results indicate that R515A delivers performance very close to that of R134A while offering a much lower global warming potential, making it the most promising replacement among the HFO blends considered for R134A applications.

Table 3(f): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R454b) for replacing High GWP eco-friendly HFC refrigerants(R410a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R454b	R410a
First law Efficiency (COP_{VCRS})	2.571	2.568
Exergy Efficiency	0.2879	0.2874
Exergy Destruction Ratio	2.474	2.530
Exergy of fuel (kW)	3.889	3.894
Exergy of Product (kW)	1.119	1.119

Table 3(f) compares R454B with R410A. The results demonstrate that R454B slightly outperforms R410A under actual operating conditions. The COP of R454B is 2.571, compared with 2.568 for R410A, while the exergy efficiency increases marginally from 0.2874 to 0.2879. In addition, the exergy destruction ratio decreases from 2.530 for R410A to 2.474 for R454B, indicating reduced system irreversibilities. The exergy of fuel required by R454B is 3.889 kW, which is marginally lower than 3.894 kW for R410A, whereas the exergy of the product remains 1.119 kW for both refrigerants. These findings demonstrate that R454B provides slightly better energy and exergy performance while significantly reducing environmental impact due to its lower GWP.

Table 3(g): Effect of eco-friendly refrigerants on actual thermal performances of simple VCRS using HFO blended Refrigerant(R454c) for replacing High GWP eco-friendly HFC refrigerants(R404a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C

Refrigerant	R454c	R404a
First law Efficiency (COP_{VCRS})	2.272	2.378
Exergy Efficiency	0.2543	0.2662
Exergy Destruction Ratio	2.932	2.757
Exergy of fuel (kW)	4.402	4.205
Exergy of Product (kW)	1.119	1.119

Table 3(g) presents the performance comparison between R454C and R404A. The results indicate that R454C exhibits slightly lower thermal performance than R404A. The COP decreases from 2.378 for R404A to 2.272 for R454C, while the exergy efficiency decreases from 0.2662 to 0.2543. The exergy destruction ratio increases from 2.757 for R404A to 2.932 for R454C, indicating greater thermodynamic irreversibilities. Likewise, the exergy of fuel increases from 4.205 kW to 4.402 kW, whereas the exergy of the product remains constant at 1.119 kW. Although R454C shows a modest reduction in energy and exergy performance compared with R404A, its substantially lower global warming potential makes it a viable environmentally friendly alternative where sustainability considerations outweigh the slight efficiency penalty.

3.3 Low GWP eco-friendly refrigerants HFO refrigerants for replacing high GWP eco-friendly refrigerants

The maximum thermal performance of vapour compression using input data for HCFO for replacingHFC-245fa & HCFC-123 refrigerants at 100% compression efficiency have been evaluated and shown in tables-4(a) respectively. It clearly shown that the HCFO -1224yd(Z) refrigerant gives slightly lower energy-exergy performance than HCFO -1224yd(Z) and HFC-245fa respectively. Although R245fa gives slightly lower thermal performance than HCFO -1224yd(Z).

Table 4(a) Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HCFO Refrigerant(R1224yd(Z)) for replacing high GWP eco-friendly HCFC &HFC refrigerants (R123& R245fa) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C

Refrigerant	*R1224 yd(Z)*	*R123*	*R245fa*
First law Efficiency (COP_{VCRS})	3.690	3.831	2.965
Exergy Efficiency	0.4131	0.4288	0.3319
Exergy Destruction Ratio	1.421	1.332	2.013
Exergy of fuel (kW)	2.71	2.61	3.373
Exergy of Product (kW)	1.119	1.119	1.119

The maximum thermal performance of vapour compression using input data for HCFO for replacingHFC-245fa & HCFC-123 refrigerants at 100% compression efficiency have been evaluated and shown in tables-4(b) respectively. It clearly shown that the HCFO -1233zd(E) refrigerant gives slightly lower energy-exergy performance than HCFO -1233zd(E) and HFC-245fa respectively. Although R245fa gives slightly lower thermal performance than HCFO -1233zd(E). The thermal performance of HCFO -1233zd(E) for replacing HCFC-123 and HFC-245fa is slightly higher than HCFO -1224yd(Z).

Table 4(b): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HCFO Refrigerant(R1233zd(E)) for replacing High GWP eco-friendly HCFC &HFC refrigerants (R123& R245fa) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C

Refrigerant	*R1233 zd(E)*	*R123*	*R245fa*
First law Efficiency (COP_{VCRS})	3.767	3.831	2.965
Exergy Efficiency	0.4217	0.4288	0.3319
Exergy Destruction Ratio	1.371	1.332	2.013
Exergy of fuel (kW)	2.655	2.61	3.373
Exergy of Product (kW)	1.119	1.119	1.119

The maximum thermal performance of vapour compression using input data for HFO-1336mzz(Z) for replacing HFC-245fa & HCFC-123 refrigerants at 100% compression efficiency have been evaluated and shown in tables-4(c) respectively. It clearly shown that the HFO-1336mzz(Z) refrigerant gives slightly lower energy-exergy performance than HFO-1336mzz(Z) and HFC-245fa respectively. Although R245fa gives slightly lower thermal performance than HFO-1336mzz(Z) The thermal performance of HCFO -1233zd(E) for replacing HCFC-123 and HFC-245fa is slightly higher than HCFO -1224yd(Z) and HFO-1336mzz(Z) respectively.

Table 4(c): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1336mzz(Z)) for replacing High GWP eco-friendly HFC refrigerants (R123& R245fa) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C

Refrigerant	*R1336 mzz(Z)*	*R123*	*R245fa*
First law Efficiency (COP_{VCRS})	3.623	3.831	2.965
Exergy Efficiency	0.4055	0.4288	0.3319
Exergy Destruction Ratio	1.466	1.332	2.013
Exergy of fuel (kW)	2.76	2.61	3.373
Exergy of Product (kW)	1.119	1.119	1.119

The maximum thermal performance of vapour compression using input data for HFO-1225ye(Z) for replacing HFC-134a & HF0-1234yf refrigerants at 100% compression efficiency have been evaluated and shown in tables-4(d) respectively. It clearly shown that the HFO-1225ye(Z) refrigerant gives slightly lower energy-exergy performance than HFC-134a. Although HFO-1234yf gives slightly lower thermal performance than HFC-134a.The thermal performance of HFO-1225ye(Z) for replacing HFO-1234yf is shown in table-4(d).

*Table 4(d): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1225ye(Z)) for replacing High GWP eco-friendly HFC refrigerants (*R134a & R1234yf*) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.*

Refrigerant	*R1225 ye(Z)*	R134a	R1234yf
COP_{VCRS}	3.406	3.492	3.226
Exergy Efficiency	0.3812	0.3909	0.3611
Exergy Destruction Ratio	1.623	1.558	1.769
Exergy of fuel (kW)	2.936	2.864	3.10
Exergy of Product (kW)	1.119	1.119	1.119

The maximum thermal performance of vapour compression using input data for HFO-1243zf for replacing HFC-134a refrigerants at 80% compression efficiency have been evaluated and shown in tables-4(e) respectively. It clearly shown that the HFO-1243zf refrigerant gives slightly lower energy-exergy performance than HFC-134a.

*Table 4(e): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1243zf) for replacing High GWP eco-friendly HFC refrigerants (*R134a*) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.*

Refrigerant	*R1243zf*	R134a
First law Efficiency (COP_{VCRS})	3.40	3.492
Exergy Efficiency	0.3806	0.3909
Exergy Destruction Ratio	1.627	1.558
Exergy of fuel (kW)	2.941	2.864
Exergy of Product (kW)	1.119	1.119

The actual thermal performance of vapour compression using input data for HFO-1234ze(E) for replacing HFC-134a refrigerants at 100% compression efficiency have been evaluated and shown in tables-5(f) respectively. It clearly shown that the HFO-1234ze(E) refrigerant gives slightly lower energy-exergy performance than HFC-134a.

Table 4(f): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1234ze(E)) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1234ze(E)*	R134a
First law Efficiency (COP_{VCRS})	3.455	3.492
Exergy Efficiency	0.3868	0.3909
Exergy Destruction Ratio	1.585	1.558
Exergy of fuel (kW)	2.894	2.864
Exergy of Product (kW)	1.119	1.119

The actual thermal performance of vapour compression using input data for HFO-1234yf for replacing HFC-134a refrigerants at 100% compression efficiency has been evaluated and shown in tables-4(g) respectively. It is clearly shown that the HFO-1234yf refrigerant gives slightly lower energy-exergy performance than HFC-134a.

Table 4(g): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant (R1234yf for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	*R1234yf*	R134a
First law Efficiency (COP_{VCRS})	3.226	3.492
Exergy Efficiency	0.3611	0.3909
Exergy Destruction Ratio	1.769	1.558
Exergy of fuel (kW)	3.10	2.864
Exergy of Product (kW)	1.119	1.119

3.4 Actual thermal performance of vapour compression refrigeration system using HFO and HCFO refrigerants

The actual thermal performance of vapour compression using input data for HCFO for replacing HFC-245fa & HCFC-123 refrigerants at 80% compression efficiency has been evaluated and shown in tables-5(a) respectively. It is clearly shown that the HCFO -1224yd(Z) refrigerant gives slightly lower energy-exergy performance than HCFO -1224yd(Z) and HFC-245fa, respectively. Although R245fa gives slightly lower thermal performance than HCFO -1224yd(Z).

The actual thermal performance of vapour compression using input data for HCFO for replacing HFC-245fa & HCFC-123 refrigerants at 80% compression efficiency has been evaluated and shown in tables-5(b) respectively. It clearly shown that the HCFO -1233zd(E) refrigerant gives slightly lower energy-exergy performance than HCFO -1233zd(E) and HFC-245fa, respectively. Although R245fa gives slightly lower thermal performance than HCFO -1233zd(E). The thermal performance of HCFO -1233zd(E) for replacing HCFC-123 and HFC-245fa is slightly higher than HCFO -1224yd(Z).

Table 5(a): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HCFO Refrigerant (R1224yd(Z)) for replacing High GWP eco-friendly HFC refrigerants (R123& R245fa) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1224 yd(Z)*	*R123*	*R245fa*
First law Efficiency (COP_{VCRS})	2.952	3.065	2.965
Exergy Efficiency	0.3305	0.3431	0.3319
Exergy Destruction Ratio	2.026	1.915	2.013
Exergy of fuel (kW)	3.387	3.263	3.373
Exergy of Product (kW)	1.119	1.119	1.119

Table 5(b): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HCFO Refrigerant(R1233zd(E)) for replacing High GWP eco-friendly HFC refrigerants (R123& R245fa) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1233 zd(E)*	*R123*	*R245fa*
First law Efficiency (COP_{VCRS})	3.014	3.065	2.965
Exergy Efficiency	0.3373	0.3431	0.3319
Exergy Destruction Ratio	1.964	1.915	2.013
Exergy of fuel (kW)	3.318	3.263	3.373
Exergy of Product (kW)	1.119	1.119	1.119

Table 5(c): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1336mzz(Z)) for replacing High GWP eco-friendly HFC refrigerants (R123& R245fa) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1336 mzz(Z)*	*R123*	*R245fa*
First law Efficiency (COP_{VCRS})	2.898	3.065	2.965
Exergy Efficiency	0.3244	0.3431	0.3319
Exergy Destruction Ratio	2.082	1.915	2.013
Exergy of fuel (kW)	3.45	3.263	3.373
Exergy of Product (kW)	1.119	1.119	1.119

The actual thermal performance of vapour compression using input data for HFO-1336mzz(Z) for replacing HFC-245fa & HCFC-123 refrigerants at 80% compression efficiency has been evaluated and shown in tables-5(c) respectively. It is clearly shown that the HFO-1336mzz(Z) refrigerant gives slightly lower energy-exergy performance than HFO-1336mzz(Z) and HFC-245fa, respectively. Although R245fa gives slightly lower thermal performance than HFO-1336mzz(Z) The thermal performance of HCFO -1233zd(E) for replacing HCFC-123 and HFC-245fa is slightly higher than HCFO -1224yd(Z) and HFO-1336mzz(Z), respectively. The maximum thermal performance of vapour compression using input data for HFO-1225ye(Z) for replacing HFC-134a & HFO-1234yf refrigerants at 80% compression efficiency has been evaluated and shown in tables-5(d), respectively. It is clearly shown that the HFO-1225ye(Z) refrigerant gives slightly lower energy-exergy performance than HFC-134a. Although HFO-1234yf gives slightly lower thermal performance than HFC-134a.The thermal performance of HFO-1225ye(Z) for replacing HFO-1234yf is shown in table-5(d) respectively.

Table 5(d): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1225ye(Z)) for replacing High GWP eco-friendly HFC refrigerants (R134a & R1234yf) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*(R1225 ye(Z))*	R134a	R1234 yf
First law Efficiency (COPVCRS)	2.724	2.794	2.581
Exergy Efficiency	0.3050	0.3127	0.2889
Exergy Destruction Ratio	2.279	2.198	2.462
Exergy of fuel (kW)	3.67	3.579	3.875
Exergy of Product (kW)	1.119	1.119	1.119

The actual thermal performance of vapour compression using input data for HFO-1243zf for replacing HFC-134a refrigerants at 80% compression efficiency have been evaluated and shown in tables-5(e) respectively. It clearly shown that the HFO-1243zf refrigerant gives slightly lower energy-exergy performance than HFC-134a.

Table 5(e): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1243zf) for replacing High GWP eco-friendly HFC refrigerants (R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1243zf*	R134a
First law Efficiency (COPVCRS)	2.720	2.794
Exergy Efficiency	0.3045	0.3127
Exergy Destruction Ratio	2.284	2.198
Exergy of fuel (kW)	3.676	3.579
Exergy of Product (kW)	1.119	1.119

The actual thermal performance of vapour compression using input data for HFO-1234ze(E) for replacing HFC-134a refrigerants at 80% compression efficiency have been evaluated and shown in tables-5(f) respectively. It clearly shown that the HFO-1234ze(E) refrigerant gives slightly lower energy-exergy performance than HFC-134a.

Table 5(g) compares the actual thermal and exergetic performance of the low-GWP refrigerant R1234yf with the conventional high-GWP refrigerant R134A under identical operating conditions at 80% isentropic compressor efficiency. The results indicate that R1234yf exhibits slightly lower thermodynamic performance than R134A while providing significant environmental advantages. The coefficient of performance (COP) of R1234yf is 2.581, compared with 2.794 for R134A, indicating that R1234yf requires slightly higher compressor work to achieve the same refrigeration capacity. Similarly, the exergy efficiency of R1234yf is 0.2889, which is lower than 0.3127 for R134A, reflecting a modest reduction in the effective utilization of available energy. The exergy destruction ratio increases from 2.198 for R134A to 2.462 for R1234yf, indicating relatively higher thermodynamic irreversibilities within the refrigeration cycle. Likewise, the exergy of fuel required by R1234yf is 3.875 kW, exceeding the 3.579 kW required by R134A, while the exergy of the product remains constant at 1.119 kW because the refrigeration load is maintained at 10 kW for both refrigerants. Although R1234yf exhibits a slight reduction in energy and exergy performance compared with R134A, its ultra-low global warming potential (GWP ≈ 1) and zero ozone depletion potential make it one of the most environmentally sustainable alternatives to R134A. Therefore, despite the small efficiency penalty, R1234yf represents a highly attractive replacement for conventional HFC refrigerants in applications where environmental regulations and long-term sustainability are the primary considerations.

Table 5(f): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant(R1234ze(E)) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1234ze(E)*	R134a
First law Efficiency (COPVCRS)	2.764	2.794
Exergy Efficiency	0.3094	0.3127
Exergy Destruction Ratio	2.232	2.198
Exergy of fuel (kW)	3.618	3.579
Exergy of Product (kW)	1.119	1.119

Table 5(g): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFO Refrigerant (R1234yf) for replacing High GWP eco-friendly HFC refrigerants (R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	*R1234yf*	R134a
First law Efficiency (COPVCRS)	2.581	2.794
Exergy Efficiency	0.2889	0.3127
Exergy Destruction Ratio	2.462	2.198
Exergy of fuel (kW)	3.875	3.579
Exergy of Product (kW)	1.119	1.119

3.5 Low GWP eco-friendly refrigerants for replacing high GWP eco-friendly refrigerants

The maximum thermal performance of vapour compression using input data for HFC-152a for replacing HFC-134a refrigerants at 100% compression efficiency has been evaluated and shown in tables-6(a) respectively. It is clearly shown that the HFC-152a refrigerant gives higher thermodynamic energy-exergy performance than HFC-134a.

Table 6(a) compares the maximum thermal and exergetic performance of the low-GWP refrigerant R152A with the conventional high-GWP refrigerant R134A under identical operating conditions at 100% isentropic compressor efficiency. The results clearly indicate that R152A outperforms R134A in both energy and exergy analyses. The coefficient of performance (COP) of R152A is 3.699, which is significantly higher than the 3.492 obtained with R134A, demonstrating that R152A produces the required refrigeration effect with lower compressor work and improved energy efficiency. Similarly, the exergy efficiency of R152A reaches 0.4141, exceeding the 0.3909 achieved by R134A, indicating more effective utilization of the available energy. The exergy destruction ratio is reduced from 1.558 for R134A to 1.415 for R152A, reflecting lower thermodynamic irreversibilities and enhanced system performance. In addition, the exergy of fuel required by R152A is 2.703 kW, which is lower than the 2.864 kW required by R134A, confirming the reduced input exergy needed to achieve the same refrigeration capacity. The exergy of the product remains constant at 1.119 kW for both refrigerants because the cooling load is maintained at 10 kW. These findings demonstrate that R152A provides superior thermodynamic performance, higher energy and exergy efficiencies, lower irreversibility, and reduced energy consumption compared with R134A. Combined with its considerably lower global warming potential, R152A emerges as a highly promising and environmentally sustainable replacement for R134A in vapour compression refrigeration systems, provided that appropriate safety measures are adopted due to its mild flammability.

Table 6 (a): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant (R152a) for replacing high-GWP eco-friendly HFC refrigerants(R134a) for reducing global warming ($T_{\_Cond}$ =50^{o}C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45^{o}C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10^{o}C (263K), isentropic compressors efficiency =100%.

Refrigerant	R152a	R134a
First law Efficiency (COP_{VCRS})	3.699	3.492
Exergy Efficiency	0.4141	0.3909
Exergy Destruction Ratio	1.415	1.558
Exergy of fuel (kW)	2.703	2.864
Exergy of Product (kW)	1.119	1.119

Table 6(b) compares the maximum thermal and exergetic performance of R245fa with the conventional high-GWP refrigerant R134A under identical operating conditions at 100% isentropic compressor efficiency. The results demonstrate that R245fa exhibits superior thermodynamic performance compared with R134A. The coefficient of performance (COP) of R245fa is 3.706, which is higher than the 3.492 obtained with R134A, indicating that R245fa achieves the required refrigeration effect with lower compressor work and improved energy efficiency. Likewise, the exergy efficiency of R245fa is 0.4148, exceeding the 0.3909 of R134A, which reflects more effective utilization of the supplied energy. The exergy destruction ratio decreases from 1.558 for R134A to 1.411 for R245fa, indicating lower thermodynamic irreversibilities and enhanced cycle performance. In addition, the exergy of fuel required by R245fa is 2.694 kW, which is lower than the 2.864 kW required by R134A, confirming that less input exergy is needed to produce the same refrigeration capacity. The exergy of the product remains constant at 1.119 kW for both refrigerants because the refrigeration load is maintained at 10 kW. Overall, the results indicate that R245fa provides higher COP, greater exergy efficiency, lower exergy destruction, and reduced energy consumption than R134A, making it a thermodynamically attractive alternative for vapour compression refrigeration systems. However, despite its improved thermal performance, the relatively high global warming potential of R245fa compared with newer HFO refrigerants should also be considered when selecting refrigerants for environmentally sustainable refrigeration applications.

Table 6(b): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFC Refrigerant (R245fa) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming ($T_{\_Cond}$ =50^{o}C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45^{o}C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10^{o}C (263K), isentropic compressors efficiency =100%.

Refrigerant	R245fa	R134a
First law Efficiency (COP_{VCRS})	3.706	3.492
Exergy Efficiency	0.4148	0.3909
Exergy Destruction Ratio	1.411	1.558
Exergy of fuel (kW)	2.694	2.864
Exergy of Product (kW)	1.119	1.119

Table 6(c): Effect of eco-friendly refrigerants on maximum thermal performances of simple vapour compression refrigeration systems using HFO blended Refrigerant(R515a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50^{o}C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45^{o}C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10^{o}C (263K), isentropic compressors efficiency =100%

Refrigerant	R32	R134a
First law Efficiency (COP_{VCRS})	3.388	3.492
Exergy Efficiency	0.3793	0.3909
Exergy Destruction Ratio	1.588	1.636
Exergy of fuel (kW)	2.897	2.951
Exergy of Product (kW)	1.119	1.119

Table 6(c) compares the maximum thermal and exergetic performance of R32 with the conventional refrigerant R134A under identical operating conditions at 100% isentropic compressor efficiency. The results indicate that the thermodynamic performance of R32 is comparable to that of R134A, although with slight variations in individual performance parameters. The coefficient of performance (COP) of R32 is 3.388, which is marginally lower than the 3.492 obtained with R134A, indicating a slightly higher compressor work requirement for the same refrigeration capacity. Similarly, the exergy efficiency of R32 is 0.3793, compared with 0.3909 for R134A, reflecting a small reduction in the effective utilization of available energy. However, the exergy destruction ratio of R32 is 1.588, which is lower than 1.636 for R134A, indicating reduced thermodynamic irreversibilities within the refrigeration cycle. Likewise, the exergy of fuel required by R32 is 2.897 kW, which is lower than the 2.951 kW required by R134A, while the exergy of the product remains constant at 1.119 kW for both refrigerants because the refrigeration capacity is maintained at 10 kW. These findings suggest that although R32 exhibits a slightly lower COP and exergy efficiency than R134A, it offers lower exergy destruction and reduced fuel exergy requirement, indicating improved thermodynamic effectiveness in terms of irreversibility

3.6 The actual thermal performance of VCRS

The actual thermal performance of vapour compression using input data for HFC-152a for replacing HFC-134a refrigerants at 80% compression efficiency have been evaluated and shown in tables-7(a) respectively. It clearly shown that the HFC-152a refrigerant gives higher thermodynamic energy-exergy performance than HFC-134a.

Table 7(a): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFC Refrigerant (R152a) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =80%.

Refrigerant	R152a	R134a
First law Efficiency (COP_{VCRS})	2.959	2.794
Exergy Efficiency	0.3313	0.3127
Exergy Destruction Ratio	2.019	2.252
Exergy of fuel (kW)	3.379	3.579
Exergy of Product (kW)	1.119	1.119

Table 7(a) compares the actual thermal and exergetic performance of R152A with the conventional refrigerant R134A under identical operating conditions at 80% isentropic compressor efficiency. The results indicate that R152A exhibits superior thermodynamic performance compared with R134A, even under actual compressor operating conditions. The coefficient of performance (COP) of R152A is 2.959, which is higher than the 2.794 obtained with R134A, indicating improved refrigeration efficiency and lower compressor work for the same cooling capacity. Similarly, the exergy efficiency of R152A is 0.3313, exceeding the 0.3127 achieved by R134A, demonstrating more effective utilization of the available energy. The exergy destruction ratio is 2.019 for R152A, which is lower than 2.252 for R134A, indicating reduced thermodynamic irreversibilities within the refrigeration cycle. Furthermore, the exergy of fuel required by R152A is 3.379 kW, compared with 3.579 kW for R134A, confirming that less input exergy is required to produce the same refrigeration effect. The exergy of the product remains constant at 1.119 kW for both refrigerants because the refrigeration load is maintained at 10 kW. These results demonstrate that R152A provides higher energy efficiency, greater exergy efficiency, lower exergy destruction, and reduced energy consumption than R134A, making it an efficient and environmentally attractive alternative for vapour compression refrigeration systems, provided that its mild flammability is appropriately addressed.

Table 7(b) presents the actual thermal and exergetic performance comparison between R245fa and R134A. The results show that R245fa also outperforms R134A under the specified operating conditions. The COP of R245fa is 2.965, compared with 2.794 for R134A, indicating a noticeable improvement in refrigeration performance. Likewise, the exergy efficiency of R245fa is 0.3319, which is higher than 0.3127 for R134A, reflecting better utilization of the supplied energy. The exergy destruction ratio decreases from 2.252 for R134A to 2.013 for R245fa, indicating lower thermodynamic irreversibilities and improved cycle effectiveness. In addition, the exergy of fuel required by R245fa is 3.373 kW, which is lower than the 3.579 kW required by R134A, while the exergy of the product remains constant at 1.119 kW because the refrigeration capacity is identical for both refrigerants. Overall, the results confirm that R245fa delivers superior energy and exergy performance compared with R134A under actual operating conditions, offering higher COP, greater exergy efficiency, lower irreversibility, and reduced input exergy. However, despite these thermodynamic advantages, the relatively higher global warming potential of R245fa compared with emerging low-GWP refrigerants should be considered when selecting refrigerants for sustainable refrigeration applications.

Table 7(b): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFC Refrigerant (R245fa) for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R245fa	R134a
First law Efficiency (COP_{VCRS})	2.965	2.794
Exergy Efficiency	0.3319	0.3127
Exergy Destruction Ratio	2.013	2.252
Exergy of fuel (kW)	3.373	3.579
Exergy of Product (kW)	1.119	1.119

The actual thermal performance of vapour compression using input data for HFC-32 for replacing HFC-134a refrigerants at 100% compression efficiency have been evaluated and shown in tables-7(c) respectively. It clearly shown that the HFC-134a refrigerant gives slightly lower thermodynamic energy-exergy performance than HFC-134a.

Table 7(c): Effect of eco-friendly refrigerants on actual thermal performances of simple vapour compression refrigeration systems using HFC Refrigerant (R32), for replacing High GWP eco-friendly HFC refrigerants(R134a) for reducing global warming for ($T_{\_Cond}$ =50°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 45°C, $Q_{\_Evap1}$ =10 kW, $T_{\_Evap1}$ = -10°C (263K), isentropic compressors efficiency =100%.

Refrigerant	R32	R134a
First law Efficiency (COP_{VCRS})	2.711	2.794
Exergy Efficiency	0.3034	0.3127
Exergy Destruction Ratio	2.296	2.252
Exergy of fuel (kW)	3.689	3.579
Exergy of Product (kW)	1.119	1.119

4. Conclusion & Recommendations

Following conclusions were drawn from present investigation

- low GWP ecofriendly HFO Blended refrigerants (R448a and R449a) can replace high GWP ecofriendly HFC refrigerants due to higher thermodynamic performances. Although thermodynamic performances of R448a is far better than R449a.

- low GWP ecofriendly HFO Blended refrigerants (R450a, R513a and R515a) can replace high GWP ecofriendly high GWP HFC-134a refrigerant Although thermodynamic performances of R450a and R513a is slightly lower than R449a
- low GWP ecofriendly HFO Blended refrigerants (R454b) can replace high GWP ecofriendly high GWP HFC-410a refrigerant Although thermodynamic performances of R450a and R454b is slightly higher than R410a
- low GWP ecofriendly HFC refrigerants (R152a, R245fa) can replace high GWP ecofriendly HFC-134a refrigerant due to higher thermodynamic performances.
- low GWP ecofriendly HFC refrigerants (R32) can replace high GWP ecofriendly HFC-134a refrigerant. Although thermodynamic performances of R32 is slightly lower than R134a.

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