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RESEARCH PAPER

Thermodynamic performance of vapour compression refrigeration system using HFOs, HCFO, HFO+HFC blended refrigerants, low GWP ecofriendly HFC refrigerants in primary circuit and nano mixed brine/glycol water in secondary circuit of evaporator

R. S. Mishra

Department of Mechanical, Production, industrial and Automobiles Engineering, Delhi Technological University, Delhi-110042

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Abstract

Low global warming potential (GWP) eco-friendly hydrofluorocarbon (HFC) refrigerants are emerging as promising replacements for conventional high-GWP HFCs due to their negligible ozone depletion potential and reduced environmental impact. The integration of nanotechnology in refrigeration systems, through the use of nano refrigerants and nano-enhanced secondary fluids, offers an effective approach to further improve thermal performance and energy efficiency. In this study, a numerical investigation is carried out on a vapor compression refrigeration (VCR) system employing low-GWP HFCs, HCFOs, and HFO–HFC blended refrigerants in the primary circuit, along with nano-mixed brine/glycol solutions in the secondary circuit of the evaporator. Nanoparticles such as Al_2O_3, TiO_2, and CuO are considered to enhance heat transfer characteristics. The results reveal that the VCR system operating with ultra-low-GWP HCFO-1233zd(E) in the primary circuit and CuO-based nano-brine in the secondary circuit exhibits the highest coefficient of performance. Additionally, systems using low-GWP HFO–HFC blends combined with TiO_2 nano-brine demonstrate significant performance improvement, highlighting their suitability for sustainable refrigeration applications.

1. Introduction

Rising global energy demand, escalating energy costs, and increasing concern over environmental degradation have intensified the need for sustainable refrigeration and air-conditioning technologies. Conventional refrigeration systems rely heavily on fossil-fuel-derived electricity and refrigerants that significantly contribute to greenhouse gas emissions and, in some cases, ozone layer depletion. As a result, refrigeration and air-conditioning sectors are under growing pressure to transition toward environmentally benign working fluids that reduce both energy consumption and adverse climatic impacts. Historically, refrigerants have evolved through multiple generations in response to environmental regulations. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), once widely used due to their favorable thermophysical properties, were phased out because of their high ozone depletion potential (ODP). Third-generation refrigerants, primarily hydrofluorocarbons (HFCs), were introduced as alternatives because they possess zero ODP. However, despite their ozone-friendly nature, many HFCs exhibit relatively high global warming potential (GWP). Consequently, HFCs are recognized as greenhouse gases and are regulated under international frameworks such as the Kyoto Protocol, the Paris Agreement, and the Kigali Amendment to the Montreal Protocol. These regulations

Corresponding author: R.S. Mishra
Email Address: rsmishra@dtu.ac.in
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mandate a gradual phase-down of high-GWP refrigerants, thereby accelerating the search for low-GWP alternatives.
In recent years, research attention has increasingly focused on fourth-generation refrigerants, commonly referred to as hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs). These refrigerants are characterized by ultra-low GWP, negligible ODP, and shorter atmospheric lifetimes compared to conventional HFCs. Due to these environmental advantages, HFOs and HCFOs are widely regarded as promising candidates for next-generation refrigeration and air-conditioning applications. However, despite their potential, many HFO-based refrigerants remain relatively underexplored, particularly with respect to their thermodynamic performance in practical refrigeration systems. Several studies have compared the performance of fourth-generation refrigerants with that of commonly used third-generation refrigerants under identical operating conditions. In many cases, HFOs have been reported to require higher mass flow rates and exhibit lower coefficients of performance (COP) than conventional HFCs for a given cooling capacity. Nevertheless, certain HFOs, such as HFO-1234ze(E), demonstrate thermodynamic behavior comparable to widely used refrigerants like R134a, while offering the additional advantage of significantly reduced GWP. This makes them attractive drop-in or near drop-in replacements in existing refrigeration systems. The urgency to adopt environmentally sustainable refrigerants has been further reinforced by recent legislative actions. For instance, the American Innovation and Manufacturing (AIM) Act of 2020 mandates a phased reduction in the production and consumption of high-GWP HFCs. Experimental investigations conducted on modular chillers have shown that some HFO/HCFO-based refrigerants and their blends can achieve substantially higher energy efficiency compared to conventional refrigerants, including ammonia-based systems. Similarly, low-GWP blended refrigerants such as R454B have demonstrated the potential to reduce greenhouse gas emissions by up to 80% in residential and light commercial air-conditioning applications. Owing to their ultra-low GWP, zero ODP, and competitive thermophysical properties, HFOs and HCFOs—often used in blends with HFCs to address safety and performance considerations—are increasingly viewed as viable replacements for high-GWP refrigerants such as R134a, R404A, R125, R236fa, and R507A. These next-generation refrigerants not only help industries comply with international environmental regulations but also offer comparable or improved heat transfer characteristics and energy efficiency. Consequently, HFO and HCFO-based refrigerants represent a promising pathway toward achieving sustainable, energy-efficient, and environmentally responsible refrigeration systems [1,2].

1.1 Eco-friendly HFO Refrigerants

Hydrofluoroolefins (HFOs) have emerged as a key class of next-generation refrigerants and working fluids due to their exceptionally low global warming potential (GWP), zero ozone depletion potential (ODP), and favorable thermophysical properties. These characteristics make HFOs attractive alternatives to conventional high-GWP hydrofluorocarbons (HFCs) in refrigeration, air conditioning, and power generation applications. In response to increasingly stringent international regulations aimed at reducing greenhouse gas emissions, HFO based fluids are being actively investigated for both vapor compression refrigeration (VCR) systems and Organic Rankine Cycle (ORC) applications. Among the promising HFOs, HFO-1336mzz(Z) (cis-$CF_3CH=CHCF_3$) has gained considerable attention as a working fluid for ORC systems operating at low-to-medium temperature heat sources. These refrigerant exhibits favorable toxicological characteristics and remains non-flammable at elevated temperatures, including 60 °C and 100 °C, addressing early concerns regarding the safety of HFO-based fluids. One of the most notable features of HFO-1336mzz(Z) is its extremely low 100-year GWP value of approximately 2, making it an environmentally sustainable alternative to traditional ORC working fluids. Despite its unsaturated molecular structure, experimental investigations have demonstrated that HFO-1336mzz(Z) maintains excellent chemical stability when exposed to common construction materials such as carbon steel, copper, and aluminum, as well as air and moisture, at temperatures up to 250 °C. Compared with both saturated and unsaturated working fluids, these refrigerant exhibits superior thermal and chemical stability, reinforcing its suitability for long-term ORC operation. Furthermore, its normal boiling point of 33.4 °C and relatively high critical temperature of 171.3 °C result in moderate vapor pressures and improved cycle efficiency, enabling effective energy conversion in low-grade heat recovery systems. Another notable fourth-generation refrigerant is HFO-1225ye(Z), which has demonstrated significant potential in vapor compression refrigeration applications, particularly for low- and ultra-low-temperature cooling. This refrigerant offers a reduced environmental footprint while maintaining satisfactory thermodynamic performance. Although its coefficient of performance (COP) is slightly lower than that of some conventional HFCs such as HFC-134a, it generally outperforms widely used low-GWP alternatives like HFO-1234yf. HFO-1225ye(Z) is especially effective in cascaded refrigeration systems, where it is commonly employed in intermediate or low-temperature stages. When paired with complementary refrigerants such as R-1233zd(E) or R-1224yd(Z), the overall system efficiency can be significantly enhanced. Additionally, the integration of nano-additives or nano-enhanced secondary fluids has been shown to further improve heat transfer and energy efficiency, making HFO-1225ye(Z) a viable option for advanced refrigeration architectures operating below −50 °C.
HFO-1243zf (3,3,3-trifluoropropene) has also been identified as a highly effective and environmentally benign substitute for traditional refrigerants. While its mild flammability necessitates adherence to appropriate safety standards, its thermodynamic performance presents substantial advantages. Numerous studies have reported that HFO-1243zf achieves a high COP in vapor compression refrigeration systems, closely matching or exceeding the performance of R134a under identical operating conditions. In air-conditioning applications, VCR systems operating with HFO-1243zf have

demonstrated higher COP values than systems using R404A, R407C, R410A, R125, and R32. Due to its similar thermophysical properties to R134a, HFO-1243zf can often be adopted as a near drop-in replacement with minimal system modifications. Furthermore, its ultra-low GWP value of approximately 1 and zero ODP make it a strong candidate for supporting global efforts to phase out high-GWP refrigerants. HFO-1234ze(E) is another widely studied low-GWP refrigerant with strong potential to replace HFC-134a in vapor compression refrigeration, heat pump, and chiller applications. This refrigerant frequently achieves COP values comparable to or slightly higher than those of R134a, particularly in medium- and high-temperature operating regimes. Its favorable thermodynamic efficiency, reduced energy consumption, and negligible environmental impact make it an attractive solution for sustainable cooling technologies. Although minor system adjustments may be required to account for pressure drop variations, HFO-1234ze(E) remains a robust and practical alternative for reducing both direct and indirect greenhouse gas emissions.

HFO-1234yf (2,3,3,3-tetrafluoroprop-1-ene) has been extensively adopted as an environmentally friendly replacement for R134a, particularly in mobile air-conditioning systems. It possesses zero ODP and an extremely low GWP, aligning well with environmental regulations. However, HFO-1234yf typically exhibits slightly lower COP, cooling capacity, and volumetric efficiency compared to R134a. Additionally, its mild flammability requires careful system design and, in some cases, the incorporation of internal heat exchangers or refrigerant blends to enhance performance. Despite these limitations, HFO-1234yf remains a critical low-GWP alternative where regulatory compliance and environmental considerations are prioritized. Recent regulatory developments in the European Union have further accelerated research into low-GWP refrigerant mixtures. Several three-component blends composed of synthetic and natural refrigerants, including R32, R41, R161, R152a, R1234ze(E), R1234yf, R1243zf, and RE170, have been proposed and theoretically evaluated. Thermodynamic analyses conducted at evaporating temperatures of 0 °C and −30 °C, with a constant condensing temperature of 30 °C, have identified optimized compositions based on performance and operational criteria. Among these, the mixture R1234yf–R152a–RE170 with a mass fraction of 0.1/0.5/0.4 has been reported as a promising candidate for replacing conventional refrigerants, offering a balanced combination of efficiency and environmental sustainability [3].

1.2 Eco-friendly HCFO Refrigerants

Hydrochlorofluoroolefins (HCFOs) have emerged as promising low-GWP alternatives to conventional hydrofluorocarbons (HFCs), particularly for high-temperature refrigeration, heat pump, and energy recovery applications. Among these, HCFO-1224yd(Z) ($CF_3CF=CHCl$) has attracted significant attention due to its ultra-low global warming potential (GWP < 1), negligible ozone depletion potential, and favorable safety characteristics. This refrigerant is classified as non-flammable (ASHRAE Class A1) and is considered a viable replacement for high-GWP working fluids such as HFC-245fa in centrifugal chillers, high-temperature heat pumps, and Organic Rankine Cycle (ORC) systems. Thermodynamic studies indicate that HCFO-1224yd(Z) can achieve comparable or improved coefficients of performance (COP) while requiring lower compressor power input, thereby enhancing overall system efficiency and reducing indirect emissions. Another widely studied HCFO refrigerant is HCFO-1233zd(E), chemically known as (E)-1-chloro-3,3,3-trifluoropropene. This next-generation refrigerant and foam blowing agent is characterized by a very low GWP (typically below 5) and negligible ODP, making it an environmentally sustainable substitute for legacy HFCs such as HFC-245fa. HCFO-1233zd(E) has demonstrated strong performance in applications including rigid foam insulation, low-pressure centrifugal chillers for commercial buildings, and ORC-based waste heat recovery systems. Classified as non-toxic and non-flammable (ASHRAE A1), it offers operational safety alongside high energy efficiency, particularly when integrated with recuperators or advanced cycle configurations.

In parallel with the development of low-impact refrigerants, enhancing the performance of vapor compression refrigeration (VCR) systems remains a critical research challenge. The incorporation of nanotechnology has introduced nanorefrigerants, which are suspensions of nanoparticles within base refrigerants, as a promising solution. Both experimental and numerical studies have shown that nanorefrigerants can significantly improve heat transfer characteristics and system performance. Reported results indicate substantial increases in COP for VCR systems when nanorefrigerants are employed, highlighting their potential to complement eco-friendly HCFO refrigerants in achieving high-efficiency, sustainable refrigeration systems [4,5].

1.3 Eco-friendly HFO Blends

Blended refrigerants based on hydrofluoroolefins (HFOs) have gained considerable attention as environmentally sustainable alternatives to conventional high-GWP refrigerants used in refrigeration and air-conditioning systems. These blends are designed to combine the favorable thermodynamic properties of established refrigerants with the ultra-low global warming potential (GWP) and zero ozone depletion potential (ODP) of HFOs, while maintaining acceptable safety classifications and system compatibility. As a result, HFO-based blends are increasingly being adopted for low- and medium-temperature refrigeration, chillers, heat pumps, and transport cooling applications.

R450A is one such low-GWP refrigerant blend developed as a replacement for R134a in refrigeration and air-conditioning systems. It is composed of R134a and HFO-1234ze(E), with mass fractions of approximately 42% and 58%, respectively. Classified as non-toxic and non-flammable (ASHRAE safety class A1), R450A provides operating characteristics similar to those of R134a while offering a substantially reduced GWP. Depending on the assessment method, its GWP is reported to be approximately 604 (IPCC AR4) or 547 (IPCC AR5), representing a significant reduction compared to R134a. Due to its comparable performance and lower environmental impact, R450A is considered suitable for chillers, heat pumps, and medium-temperature refrigeration systems with minimal system modifications. Another widely used low-GWP blend is R513A, which is composed of R1234yf and R134a. This refrigerant has zero ODP and approximately half the GWP of R134a, making it a future-proof alternative under international regulations such as the Kigali Amendment. Although R513A may require slightly higher mass flow rates and can exhibit marginally lower coefficients of performance (COP) in certain systems, it remains a non-flammable (A1) and broadly compatible substitute for medium-temperature applications. In many cases, R513A can be implemented with only minor system adjustments, facilitating a smooth transition away from high-GWP refrigerants.

Honeywell Solstice R515A is another HFO-based blend developed as an environmentally friendly replacement for R134a. Composed primarily of HFO-1234ze(E) with a smaller fraction of R227ea, R515A is classified as non-flammable (A1) and has zero ODP. It offers relatively high cooling capacity and stable operation, making it particularly suitable for medium-temperature chiller applications. Its low GWP and favorable safety profile make it an attractive option for meeting increasingly stringent environmental regulations.

In addition to R134a replacements, several HFO-based blends have been proposed to substitute high-GWP refrigerants such as R404A, R22, and R410A. Blends containing R32 and R1234yf, including R454A, R454B, and R454C, have been extensively investigated for low- and medium-temperature refrigeration. R454A and R454C differ in composition but share the advantage of significantly reduced GWP compared to conventional refrigerants. R454C, composed mainly of R1234yf with a smaller fraction of R32, exhibits a GWP of approximately 145–148, which is dramatically lower than that of R404A. This reduction makes R454C a promising alternative for low- and medium-temperature refrigeration systems, particularly where compliance with strict environmental regulations such as the European Union F-Gas Regulation is required. Polyol ester (POE) oil is commonly used as the preferred lubricant for these blends, ensuring compatibility with existing compressor technologies.

Extensive research has been conducted on the thermodynamic and exergetic performance of eco-friendly HFO blends in vapor compression refrigeration (VCR) systems. These studies often focus on energy efficiency, exergy destruction, and environmental impact, particularly for ultra-low-temperature applications using cascaded refrigeration systems. Blends incorporating refrigerants such as R1233zd(E), R1224yd(Z), and R41 have demonstrated improved performance in specific temperature stages, offering enhanced efficiency and reduced emissions compared to conventional refrigerants. Furthermore, investigations combining HFO and HFC components have reported promising results in terms of system performance and environmental sustainability [6]. Recent studies also highlight the growing importance of nano-enhanced refrigeration systems. Although significant progress has been made, further research is needed to fully understand condensation heat transfer characteristics of nanorefrigerants. Metal oxide nanoparticles such as Al_2O_3, TiO_2, and CuO have been identified as effective additives capable of enhancing thermal conductivity and overall system performance. The combined application of ultra-low-GWP HFO and HCFO refrigerants in the primary circuit of the evaporator, along with nano-enhanced brine flows in the secondary circuit, has been shown to improve both first- and second-law performance of refrigeration systems, reinforcing their potential for sustainable cooling technologies [7–9].

2. Proposed Model

Figure 1 illustrates the proposed model adopted for the present investigation. The system is based on a chiller operating with a simple vapor compression refrigeration system (VCRS) configuration. The evaporator and condenser are designed as concentric copper tube heat exchangers to ensure effective heat transfer. In the evaporator, the refrigerant flows through the inner tube and acts as the primary circuit, while the brine or glycol solution circulates through the annular region as the secondary circuit. In the condenser, cooling water is supplied through the inner tube, whereas the refrigerant flows through the annulus.

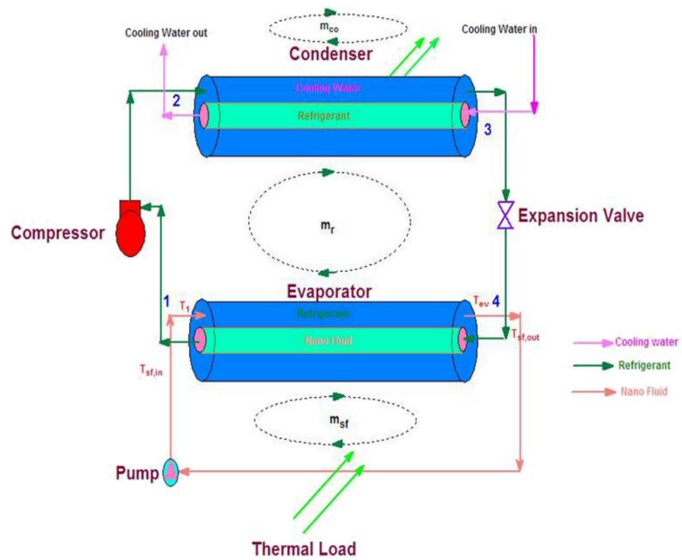

Figure 1: Schematic structure of model

The model evaluates the thermodynamic performance of the VCRS by considering several operating and geometric input parameters. These include inlet temperature of the brine or glycol, condenser water inlet temperature, compressor speed (rpm), refrigerant type, mass flow rates of refrigerant, brine, and water, along with the structural parameters of the evaporator and condenser. Using these inputs, the coefficient of performance (COP) of the system is determined. For simulations involving nanorefrigerants, variables such as nanoparticle type, particle diameter, and thermophysical properties are incorporated to assess influence effects.

3. Results and Discussion

The thermal performance of the proposed vapor compression refrigeration system (VCRS) is evaluated using the operating conditions and geometric parameters listed in Table 1. The analysis is carried out for the system configuration illustrated in Figure 1. The evaporator and condenser tube lengths are fixed at 8 m and 12 m, respectively. The mass flow rate of the secondary fluid (brine/glycol) circulating through the evaporator is varied from 0.006 to 0.008 kg/s, while the condenser cooling water flow rate is maintained within the range of 0.006 to 0.010 kg/s. To ensure consistent boundary conditions, the inlet temperatures of both the evaporator secondary fluid and the condenser cooling water are kept constant at 27 °C.

The coefficient of performance (COP), representing the first-law thermodynamic efficiency of the VCR system, is numerically computed for different combinations of refrigerants and secondary working fluids. The primary circuit of the evaporator employs various low-GWP refrigerants, including HFOs, HCFOs, HFO–HFC blended refrigerants, and eco-friendly HFCs. In parallel, the secondary circuit of the evaporator is analyzed using brine/glycol solutions with and without the addition of three different nanomaterials. The numerical results obtained highlight the combined influence of refrigerant selection and nano-enhanced secondary fluids on system performance. Detailed comparisons and performance trends are discussed in the subsequent subsections.

Table 1:Operating and geometric input parameters used for the thermodynamic performance analysis of the vapor compression refrigeration system.

S. N	Input parameters	value
1	Length of evaporator (m)	8.
2	Length of condenser tubes (m)	12
3	Mass flow of brine/glycol (kg/s)	0.006- 0.008
4	Mass flow rate of condenser water (kg/s)	0.006-0.010
5	Temperature of evaporator Brine flow	27^{o}C
6	Temperature of condenser water flow rate	27^{o}C

3.1 Thermodynamic performances of ultra-low GWP eco-friendly HFO refrigerants with nanomaterials mixed in brine secondary circuit of evaporator and without nanofluids

Hydrofluoroolefins (HFOs) are widely recognized as next-generation refrigerants capable of replacing conventional high-GWP hydrofluorocarbons (HFCs) due to their negligible ozone depletion potential (ODP) and extremely low global warming potential (GWP). Among them, refrigerants such as R-1234yf are already extensively used in automotive air-conditioning systems. However, the thermodynamic performance of certain HFOs may be marginally lower than that of traditional HFCs under similar operating conditions. To overcome this limitation, the application of nanorefrigeration technology—through the use of nano-enhanced secondary fluids—has emerged as an effective approach to improve heat transfer and overall system efficiency. In the present analysis, the first-law thermodynamic performance of the vapor compression refrigeration system is evaluated using different ultra-low-GWP HFO refrigerants in the primary circuit of the evaporator, while brine mixed with metal-oxide nanoparticles (CuO, Al_2O_3, and TiO_2) is employed in the secondary circuit. The coefficient of performance (COP) obtained with nano-enhanced brine is compared against the baseline case using pure brine. The numerical results corresponding to HFO-1234ze(E), HFO-1234yf, HFO-1243zf, HFO-1225ye(Z), and HFO-1336mzz(Z) are summarized in Tables 2(a)–2(e), respectively.

As shown in Table 2(a), the incorporation of nanoparticles in the brine significantly enhances the COP of the system operating with HFO-1234ze(E), with CuO-based nanofluid yielding the highest improvement. Similar enhancement trends are observed for HFO-1234yf, as presented in Table 2(b), although this refrigerant exhibits comparatively lower COP values and higher compressor power consumption among the HFOs investigated. The performance results for HFO-1243zf in Table 2(c) demonstrate notable COP enhancement with nano-enhanced brine, particularly with CuO and Al_2O_3 nanoparticles. Table 2(d) indicates that HFO-1225ye(Z) also benefits substantially from the addition of nanoparticles, achieving appreciable performance gains over the base brine case. Among all the refrigerants studied, HFO-1336mzz(Z) combined with CuO-based nano-brine exhibits the highest COP and the lowest compressor power requirement, as shown in Table 2(e). Conversely, the lowest thermodynamic performance is observed for HFO-1234yf when TiO_2-based nanofluid is used. Overall, the results confirm that the integration of nano-enhanced secondary fluids significantly improves the thermodynamic performance of ultra-low-GWP HFO refrigerants. These findings highlight the strong potential of HFO-based refrigeration systems, supported by nanotechnology, as sustainable and energy-efficient alternatives to high-GWP HFC refrigerants.

Table 2(a): Thermodynamic performances of HFO-1234ze (E) refrigerant.

Eco-friendly HFO-1234ze(E) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhance-ment
$COP\__{without\ Nano}$	Brine	3.019	--
$COP\__{with}$	Brine with mixed CuO_{Nano}	3.601	19.278
$COP\__{with\ Nano}$	Brine with mixed $Al_2O_{3\ Nano}$	3.485	15.436
$COP\__{with\ Nano}$	Brine with mixed $TiO_{2\ Nano}$	3.335	10.467

Table 2(b): Thermodynamic performances of HFO-1234yf refrigerant

Eco-friendly HFO-1234yf Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP_{\_without\ Nano}$	Brine	2.901	--
$COP_{\_with}$	Brine with mixed CuO $_{Nano}$	3.415	17.718
$COP_{\_with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.285	13.238
$COP_{\_with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.235	11.513

Table 2(c): Thermodynamic performances of HFO-1243zf refrigerant

Eco-friendly HFO-1243zf Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP_{\_without\ Nano}$	Brine	2.966	--
$COP_{\_with}$	Brine with mixed CuO $_{Nano}$	3.510	18.340
$COP_{\_with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.415	15.138
$COP_{\_with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.215	8.395

Table 2(d): Thermodynamic performances of HFO-1225ye(Z) refrigerants

Eco-friendly HFO-1225ye(Z) Refrigerants	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP_{\_without\ Nano}$	Brine	3.0189	--
$COP_{\_with}$	Brine with mixed CuO $_{Nano}$	3.5789	18.55
$COP_{\_with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.4853	15.50
$COP_{\_with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.335	10.467

Table 2(e): Thermodynamic performances of HFO-1336mzz(Z) refrigerant

Eco-friendly HFO-1336mzz(Z) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP_{\_without\ Nano}$	Brine	3.061	--
$COP_{\_with}$	Brine with mixed CuO $_{Nano}$	3.705	21.040
$COP_{\_with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.585	17.1186
$COP_{\_with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.485	10.460

3.2 Thermodynamic performances of ultra-low GWP eco-friendly HCFO refrigerants with and without nanofluids

Hydrochlorofluoroolefins (HCFOs) have emerged as promising low-GWP refrigerants capable of replacing conventional hydrofluorocarbons (HFCs), owing to their significantly reduced ozone depletion potential (ODP) and global warming potential (GWP). Despite their environmental advantages, further improvement in the thermal performance of HCFO-based refrigeration systems is desirable to ensure their competitiveness with existing refrigerants. In this context, the application of nanotechnology through the use of nano-enhanced secondary working fluids offers an effective means to intensify heat transfer and improve system efficiency. In the present study, the thermodynamic performance of a vapor compression refrigeration system operating with ultra-low-GWP HCFO refrigerants is investigated using nano-enhanced brine in the secondary circuit of the evaporator. The coefficient of performance (COP) obtained with pure brine is compared with that achieved using brine mixed with metal-oxide nanoparticles, namely CuO, Al_2O_3, and TiO_2. The detailed performance data for HCFO-1224yd(Z) and HCFO-1233zd(E) are summarized in Tables 3(a) and 3(b), respectively. As evident from Table 3(a), the introduction of nanoparticles into the brine markedly improves the COP of the system operating with HCFO-1224yd(Z). Among the tested nanofluids, CuO-based nano-brine provides the highest enhancement in thermodynamic performance, followed by Al_2O_3 and TiO_2 nanofluids. A similar trend is observed for HCFO-1233zd(E), as presented in Table 3(b), where the use of nano-enhanced brine results in a substantial increase in COP compared to the baseline case without nanoparticles. The maximum COP and minimum compressor power consumption are achieved when HCFO-1233zd(E) is combined with CuO-mixed nano-brine.

Table 3(a): Thermodynamic performances of HCFO-1224yd (Z) refrigerant

Eco-friendly HCFO-1224yd(Z) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP_{\_without\ Nano}$	Brine	3.063	--
$COP_{\_with}$	Brine with mixed CuO $_{Nano}$	3.715	21.286
$COP_{\_with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.585	17.29
$COP_{\_with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.435	12.145

Table 3(b): Thermodynamic performances of HCFO-1224yd (Z) refrigerant

Eco-friendly HCFO-1233zd(E) Refrigerants	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP_{\_without\ Nano}$	Brine	3.155	--
$COP_{\_with}$	Brine with mixed CuO $_{Nano}$	3.845	21.870
$COP_{\_with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.785	19.96
$COP_{\_with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.585	12.361

3.3 *Thermodynamic performances of ultra-low GWP eco-friendly HFO+HFC blended refrigerants with and without nanofluids*

Blends of hydrofluoroolefins (HFOs) and hydrofluorocarbons (HFCs) are increasingly considered as transitional refrigerants because they combine reduced global warming potential with acceptable thermophysical properties and system compatibility. However, to further improve their energy efficiency, the application of nano-enhanced secondary working fluids in the evaporator circuit has gained significant attention. The dispersion of metal-oxide nanoparticles such as CuO, Al_2O_3, and TiO_2 in brine enhances thermal conductivity and convective heat transfer, which directly contributes to improved system performance.

In this study, the thermodynamic behavior of a vapor compression refrigeration system operating with ultra-low-GWP HFO–HFC blended refrigerants is evaluated using nano-enhanced brine in the secondary circuit of the evaporator. The system performance, expressed in terms of the coefficient of performance (COP), is analyzed for five different refrigerant blends, namely R450A, R513A, R515A, R454B, and R454C. The detailed numerical results for these refrigerants are presented in Tables 4(a)–4(e).

As shown in Tables 4(a) and 4(b), both R450A and R513A exhibit a notable increase in COP when nano-enhanced brine is employed, with CuO-based nanofluids producing the highest performance enhancement, followed by Al_2O_3 and TiO_2 nanofluids. A similar improvement trend is observed for R515A, as presented in Table 4(c), where the combination of R515A and CuO-mixed nano-brine delivers the highest thermodynamic performance among all tested HFO–HFC blends, accompanied by the lowest compressor power consumption.

The performance results for R454B and R454C, summarized in Tables 4(d) and 4(e), indicate comparatively lower COP values than those of R450A, R513A, and R515A under identical operating conditions. Among these blends, R454C combined with TiO_2-based nano-brine exhibits the lowest thermodynamic performance and the highest compressor power requirement. Nevertheless, even in these cases, the introduction of nanoparticles leads to measurable improvements over the base fluid operation without nanomaterials.

Table 4(a)*: Thermodynamic performance of ecofriendly HFO+HFC blended* (R450a) *refrigerant*

Eco-friendly HFO+HFC blended (R450a) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	2.987	--
$COP\_{with\ Nano}$	Brine with mixed CuO $_{Nano}$	3.556	19.058
$COP\_{with\ Nano}$	Brine with mixedAl_2O_3 $_{Nano}$	3.4365	15.05
$COP\_{with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.287	10.05

Table 4(b)*: Thermodynamic performance of ecofriendly HFO+HFC blended* (R513a*) refrigerant*

Eco-friendly HFO+HFC blended (R513a) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	2.960	--
$COP\_{with\ Nano}$	Brine with mixed CuO $_{Nano}$	3.527	19.158
$COP\_{with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.417	15.426
$COP\_{with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.2607	10.165

Table 4(c)*: Thermodynamic performance of ecofriendly HFO+HFC blended (R515a) refrigerant*

Eco-friendly HFO+HFC blended (R515a) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	3.015	--
$COP\_{with\ Nano}$	Brine with mixed CuO $_{Nano}$	3.592	19.136
$COP\_{with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.471	15.136
$COP\_{with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.325	10.265

Table 4(d)*: Thermodynamic performance of ecofriendly HFO+HFC blended (R454b) refrigerant*

Eco-friendly HFO+HFC blended (R454b) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	2.857	--
$COP\_{with\ Nano}$	Brine with mixed CuO $_{Nano}$	3.362	17.683
$COP\_{with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.252	13.830
$COP\_{with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	3.122	9.265

Table 4(e)*: Thermodynamic performance of ecofriendly HFO+HFC blended (R454c) refrigerant*

Eco-friendly HFO+HFC blended (R454c) Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	2.7059	--
$COP\_{with\ Nano}$	Brine with mixed CuO $_{Nano}$	3.119	15.275
$COP\_{with\ Nano}$	Brine with mixed Al_2O_3 $_{Nano}$	3.0432	12.467
$COP\_{with\ Nano}$	Brine with mixed TiO_2 $_{Nano}$	2.9082	7.475

3.4 Thermodynamic performances of low GWP eco-friendly HFC refrigerants with and without nanofluids

Low global warming potential (GWP) hydrofluorocarbon (HFC) refrigerants are increasingly being investigated as environmentally acceptable substitutes for conventional high-GWP HFCs. In the present analysis, the thermodynamic performance of a vapor compression refrigeration system operating with low-GWP HFC refrigerants is evaluated using nano-enhanced brine as the secondary fluid in the evaporator. The addition of metal-oxide nanoparticles such as CuO, Al_2O_3, and TiO_2 to the brine is intended to improve heat transfer characteristics and, consequently, the overall system efficiency. The numerical results obtained for HFC-152a, HFC-245fa, HFC-32, and HFC-134a are summarized in Tables 5(a)–5(d). As observed from Table 5(a), the use of CuO-based nano-brine with HFC-152a results in the highest coefficient of performance (COP) among all the low-GWP HFC refrigerants considered, along with the lowest compressor power consumption. A similar enhancement trend is evident for HFC-245fa, as shown in Table 5(b), where CuO nanoparticles again provide the maximum improvement, followed by Al_2O_3 and TiO_2 nanofluids. The performance results for HFC-32, presented in Table 5(c), indicate comparatively lower COP values under identical operating conditions, particularly when TiO_2-based nano-brine is employed. Among the tested refrigerants, HFC-32 combined with TiO_2-mixed nano-brine exhibits the lowest thermodynamic performance and the highest compressor energy requirement. The results for HFC-134a, given in Table 5(d), demonstrate moderate performance enhancement with nano-brine, although its COP remains lower than that of HFC-152a and HFC-245fa.

Table 5(a): Thermodynamic performance of low GWP eco-friendly HFC-152arefrigerant

Eco-friendly HFC-152a Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	3.075	--
COP_{with}	Brine with mixed CuO $_{Nano}$	3.699	20.30
$COP\_{with\ Nano}$	Brine with mixed $Al_2O_{3\ Nano}$	3.552	15.55
$COP\_{with\ Nano}$	Brine with mixed $TiO_{2\ Nano}$	3.40	10.57

Table 5(b): Thermodynamic performance of low GWP eco-friendly HFC -245fa refrigerant

Eco-friendly HFC-245fa Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	3.085	--
$COP\_{withnano}$	Brine with mixed CuO $_{Nano}$	3.6820	19.35
$COP\_{with\ Nano}$	Brine with mixed $Al_2O_{3\ Nano}$	3.5678	15.65
$COP\_{with\ Nano}$	Brine with mixed $TiO_{2\ Nano}$	3.4085	10.487

Table 5(c): Thermodynamic performance of low GWP eco-friendly HFC-32 refrigerant

Eco-friendly HFC-32Refrigerants	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	2.987	--
COP_{with}	Brine with mixed CuO $_{Nano}$	3.560	19.18
$COP\_{with\ Nano}$	Brine with mixed $Al_2O_{3\ Nano}$	3.430	14.87
$COP\_{with\ Nano}$	Brine with mixed $TiO_{2\ Nano}$	3.300	10.487

Table 5(d): Thermodynamic performance of low GWP eco-friendly HFC-134a refrigerant

Eco-friendly HFC-245fa Refrigerant	Types of Nano mixed media	First law Efficiency (COP)	% Enhancement
$COP\_{without\ Nano}$	Brine	3.020	--
$COP\_{with\ Nano}$	Brine with mixed CuO $_{Nano}$	3.6018	19.265
$COP\_{with\ Nano}$	Brine with mixed $Al_2O_{3\ Nano}$	3.487	15.460

3.5 Thermodynamic performances of ultra-low GWP eco-friendly HFO refrigerants with nanomaterials mixed in Glycol-water of secondary circuit of evaporator and without nanofluids

The thermodynamic behavior of a vapor compression refrigeration system operating with ultra-low global warming potential (GWP) HCFO refrigerants was investigated using glycol-water as the secondary fluid in the evaporator, both with and without nanoparticle enhancement. The objective of this analysis is to assess the influence of metal-oxide nanoparticles on system efficiency and compressor energy consumption. The computed performance results for HCFO-1224yd (Z) and HCFO-1233zd (E) are presented in Tables 7(a) and 7(b), respectively. As evident from Table 7(a), the incorporation of CuO nanoparticles into the glycol-water mixture significantly enhances the coefficient of performance (COP) of the system when HCFO-1224yd (Z) is employed as the primary refrigerant. Among the tested nanofluids, CuO-based nano-glycol water yields the maximum COP improvement, followed by Al_2O_3 and TiO_2 nanoparticles. However, the lowest thermodynamic performance for HCFO-1224yd (Z) is observed when TiO_2-mixed glycol-water is used, resulting in comparatively higher compressor power consumption. A similar enhancement trend is observed for HCFO-1233zd (E), as summarized in Table 7(b). The results indicate that HCFO-1233zd (E) combined with CuO-mixed glycol-water provides the highest COP among all cases considered in this section, along with the minimum compressor energy requirement. Al_2O_3-based nanofluid also offers performance improvement.

Table-7(a): Thermodynamic performance of ultra low GWP eco-friendly HCFO-1224yd (Z)refrigerant

Eco-friendly HCFO-1224yd (Z) Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhancement
COP_without Nano	Glycol-water	2.8965	--
COP_with	Glycol-water with mixed CuO Nano	3.469	19.75
COP_with Nano	Glycol-water with mixed Al_2O_3 Nano	3.344	15.45
COP_with Nano	Glycol-water with mixed TiO_2 Nano	3.1992	10.45

Table-7(b): Thermodynamic performance of ultra low GWP eco-friendly HCFO-1233zd (E)refrigerant

Eco-friendly HFO-1233zd (E) Refrigerants	Types of Nano mixed media	First law Efficiency	% Enhancement
COP_without Nano	Glycol-water	2.975	--
COP_with	Glycol-water with mixed CuO Nano	3.563	19.76
COP_with Nano	Glycol-water with mixed Al_2O_3 Nano	3.436	15.50
COP_with Nano	Glycol-water with mixed TiO_2 Nano	3.286	10.45

3.6 Thermodynamic performances of ultra low GWP eco-friendly HFO+HFC blended refrigerants with nano materials mixed in Glycol-water of secondary circuit of evaporator and without nanofluids

Blended refrigerants composed of hydrofluoroolefins (HFOs) and hydrofluorocarbons (HFCs), combined with nano-enhanced secondary fluids, represent a promising approach for improving the efficiency and sustainability of vapor compression refrigeration systems. These blends offer reduced Global Warming Potential (GWP) while maintaining favorable thermodynamic characteristics. The addition of metal-oxide nanoparticles such as CuO, Al_2O_3, and TiO_2 to glycol–water in the evaporator secondary circuit further enhances heat transfer by increasing thermal conductivity and reducing flow resistance, thereby improving system performance.

The thermodynamic performance results obtained using HFO+HFC blended refrigerants with nano-enhanced glycol–water are summarized in Tables 8(a) to 8(e). As shown in Table 8(a), the R450A refrigerant exhibits a noticeable improvement in coefficient of performance (COP) when nanoparticles are introduced, with the CuO-based nanofluid providing the highest enhancement. A similar trend is observed for R513A, as presented in Table 8(b), where CuO-mixed glycol–water yields the maximum COP improvement, followed by Al_2O_3 and TiO_2 nanoparticles.

Among all the blended refrigerants analyzed, R515A demonstrates superior thermodynamic behavior, as indicated in Table 8(c). When combined with CuO-based nano-glycol water, R515A achieves the highest COP and the lowest compressor power consumption across this group of refrigerants. In contrast, the performance of R454B, presented in Table 8(d), shows comparatively lower COP values, although the inclusion of nanomaterials still results in measurable performance gains relative to the base glycol–water case.

Table 8(a): Thermodynamic performance of ultra low GWP eco-friendly HFO+HFC blended refrigerant

Eco-friendly HFO+HFC blended (R450a) Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhancement
COP_without Nano	Glycol-water	2.857	--
COP_with Nano	Glycol-water with mixed CuO Nano	3.401	19.05
COP_with Nano	Glycol-water with mixed Al_2O_3 Nano	3.286	15.014
COP_with Nano	Glycol-water with mixed TiO_2 Nano	3.142	9.465

Table 8(b): Thermodynamic performance of ultra low GWP eco-friendly HFO+HFC blended (R-513a) *refrigerant*

Eco-friendly HFO+HFC blended (R513a) Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhance-ment
COP_without Nano	Glycol-water	2.830	--
COP_with Nano	Glycol-water with mixed CuO Nano	3.340	18.056
COP_with Nano	Glycol-water with mixed Al_2O_3 Nano	3.247	14.736
COP_with Nano	Glycol-water with mixed TiO_2 Nano	3.088	9.136

Table 8(c): Thermodynamic performance of ultra low GWP eco-friendly HFO+HFC blended (R-515a) *refrigerant*

Eco-friendly HFO+HFC blended (R515a) Refrigerants	Types of Nano mixed media	First law Efficiency	% Enhancement
COP_without Nano	Glycol-water	2.875	--
COP_with Nano	Glycol-water with mixed CuO Nano	3.426	19.165
COP_with Nano	Glycol-water with mixed Al_2O_3 Nano	3.311	15.165
COP_with Nano	Glycol-water with mixed TiO_2 Nano	3.1812	10.065

Table 8(d)*: Thermodynamic performance of ultra low GW eco-friendly HFO+HFC blended (R-454b) refrigerant*

Eco-friendly HFO+HFC blended (R454b) Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhance-ment
COP_without Nano	Glycol-water	2.675	--
COP_with Nano	Glycol-water with mixed CuO Nano	3.137	17.275
COP_with Nano	Glycol-water with mixed Al_2O_3 Nano	3.007	12.415
COP_with Nano	Glycol-water with mixed TiO_2 Nano	2.869	7.265

Table 8(e): Thermodynamic performance of ultra-low GWP eco-friendly HFO+HFC blended (R-454c) refrigerant

Ecofriendly HFO+HFC blended (R454c) Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhance-ment
$COP_{\_without\ Nano}$	Glycol-water	2.558	--
$COP_{\_with\ Nano}$	Glycol-water with mixed CuO_{Nano}	2.935	14.75
$COP_{\_with\ Nano}$	Glycol-water with mixed $Al_2O_{3\ Nano}$	2.866	12.0375
$COP_{\_with\ Nano}$	Glycol-water with mixed $TiO_{2\ Nano}$	2.7413	7.165

The lowest thermodynamic performance among the investigated blends is observed for R454C, as reported in Table 8(e). In particular, the use of TiO_2-mixed glycol–water with R454C results in the minimum COP and the highest compressor energy requirement, indicating a comparatively weaker enhancement effect

3.7 Thermodynamic performances of low GWP eco-friendly HFC refrigerants with nanomaterials mixed in Glycol-water of secondary circuit of evaporator and without nanofluids

Low Global Warming Potential (GWP) hydrofluorocarbon (HFC) refrigerants combined with nano-enhanced secondary fluids offer a viable pathway for improving the energy efficiency of vapor compression refrigeration systems while reducing environmental impact. The incorporation of metal-oxide nanoparticles such as CuO, Al_2O_3, and TiO_2 into glycol–water circulating in the evaporator secondary circuit enhances thermal conductivity and heat transfer characteristics, resulting in improved system performance and reduced compressor power consumption. The thermodynamic performance results for low-GWP HFC refrigerants operating with nano-enhanced glycol–water are presented in Tables 9(a) to 9(d). As shown in Table 9(a), the HFC-152a refrigerant exhibits the highest coefficient of performance (COP) among the investigated refrigerants when CuO-based nanofluid is used, achieving the maximum enhancement relative to the base glycol–water case. The use of Al_2O_3 and TiO_2 nanoparticles also improves system performance, although to a lesser extent.

Table 9(b) presents the performance of HFC-245fa, where the addition of CuO nanoparticles again results in the greatest COP improvement, followed by Al_2O_3 and TiO_2. Similar enhancement trends are observed for HFC-32, as summarized in Table 9(c). Although HFC-32 shows noticeable performance gains with nano-enhanced glycol–water, its overall COP remains lower than that of HFC-152a and HFC-245fa under comparable operating conditions. The thermodynamic behavior of HFC-134a is reported in Table 9(d). While the inclusion of nanoparticles improves the COP relative to the base fluid, the magnitude of enhancement is comparatively smaller than that observed for other low-GWP HFC refrigerants. Among all the cases studied, HFC-32 combined with TiO_2-based nanofluid results in the lowest COP and the highest compressor power requirement.

Table 9(a): Thermodynamic performance of low GWP eco-friendly HFC-152arefrigerant

Eco-friendly HFC-152a Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhance-ment
$COP_{\_without\ Nano}$	Glycol-water	2.915	--
$COP_{\_with}$	Glycol-water with mixed CuO_{Nano}	3.714	20.78
$COP_{\_with\ Nano}$	Glycol-water with mixed $Al_2O_{3\ Nano}$	3.560	15.575
$COP_{\_with\ Nano}$	Glycol-water with mixed $TiO_{2\ Nano}$	3.40	10.575

Table 9(b): Thermodynamic performance of low GWP ecofriendly HFC-245farefrigerant

Eco-friendly HFC-245fa Refrigerant	Types of Nano mixed media	First law Efficiency	% Enhance-ment
$COP_{\_without\ Nano}$	Glycol-water	2.920	--
$COP_{\_with}$	Glycol-water with mixed CuO_{Nano}	3.5055	20.051
$COP_{\_with\ Nano}$	Glycol-water with mixed $Al_2O_{3\ Nano}$	3.399	16.390
$COP_{\_with\ Nano}$	Glycol-water with mixed $TiO_{2\ Nano}$	3.226	10.475

Table 9(c): Thermodynamic performance of low GWP eco-friendly HFC-32refrigerant

Eco-friendly HFC-32 Refrigerants	Types of Nano mixed media	First law Efficiency	% Enhance-ment
$COP_{\_without\ Nano}$	Glycol-water	2.852	--
$COP_{\_with}$	Glycol-water with mixed CuO_{Nano}	3.532	18.250
$COP_{\_with\ Nano}$	Glycol-water with mixed $Al_2O_{3\ Nano}$	3.439	15.140
$COP_{\_with\ Nano}$	Glycol-water with mixed $TiO_{2\ Nano}$	3.288	10.075

Table 9(d): Thermodynamic performance of low GWP eco-friendly HFC-134 a refrigerant

Eco-friendly HFC-134a Refrigerants	Types of Nano mixed media	First law Efficiency	% Enhance-ment
$COP_{\_without\ Nano}$	Brine	2.885	--
$COP_{\_with\ Nano}$	Brine with mixed CuO_{Nano}	3.360	16.459
$COP_{\_with\ Nano}$	Brine with mixed $Al_2O_{3\ Nano}$	3.273	13.456
$COP_{\_with\ Nano}$	Brine with mixed $TiO_{2\ Nano}$	3.135	8.67

4. Conclusion

Based on the thermodynamic investigation of a vapor compression refrigeration system (VCRS) operating with eco-friendly refrigerants and nano-enhanced secondary fluids, the following conclusions are drawn:

- The first-law (energy) performance of the VCR system is significantly enhanced when the eco-friendly refrigerant HCFO-1233zd(E) is employed in the primary circuit and CuO nanoparticles are dispersed in brine as the secondary working fluid of the evaporator. Under identical operating conditions, a maximum COP improvement of approximately 21.87% is achieved. A slightly lower enhancement is observed when HCFO-1224yd(Z) is used with the same nano-brine configuration.
- The use of eco-friendly HFO and HCFO blended refrigerants combined with CuO, Al_2O_3, and TiO_2 nanoparticles dispersed in glycol–water further improves the first-law efficiency of the VCR system. The maximum enhancement recorded is approximately 19.76%, while comparatively lower performance is obtained when HCFO-1224yd(Z) operates with CuO-based nanofluid in the evaporator secondary circuit.
- For identical operating conditions and nano-enhanced secondary fluids, HCFO-1224yd(Z) demonstrates higher COP than HFO-1336mzz(Z). Moreover, R-1233zd(E) consistently delivers superior first-law performance compared to HCFO-1224yd(Z) when CuO nanoparticles are mixed with either brine or glycol–water in the evaporator secondary circuit.
- Refrigerants HFO-1243zf, R-1234yf, and R-1225ye(Z) operating in the primary circuit exhibit lower thermodynamic performance than R-152a and R-245fa when any nanoparticle-based glycol–water mixture is used in the secondary circuit. The reduction in COP is observed to be in the range of 5% to 10.7% when compared with nano-brine-based configurations.
- The first-law (energy) performance of the VCR system using low-GWP HFC refrigerants is notably improved by dispersing CuO nanoparticles in brine as the evaporator secondary fluid. Among the tested refrigerants, R-152a exhibits the highest enhancement, with a maximum COP improvement of approximately 20.3%.
- The thermodynamic performance of eco-friendly HFO+HFC blended refrigerants is consistently higher when nano-enhanced brine is used in the secondary circuit compared to nano-enhanced glycol–water. The lowest performance is observed for R-454c operating with TiO_2-based glycol–water nanofluid in the evaporator.
- When replacing conventional R-134a, the use of Al_2O_3-based nanofluids results in COP improvements of approximately 8.2% for R-1233zd(E), 5.8% for R-1224yd(Z), and 3% for HFO-1336mzz(Z), indicating their strong potential as low-GWP alternatives.

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