International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

ORIGINAL ARTICLE

Thermophysical property of nano-refrigerant: preparation, thermal characteristics, and applications in the VCR system using HFCO and HFO refrigerants in primary circuit and glycol based nano refrigerants in secondary circuit

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Article Information

Received: 29 October 2023
Revised: 17 November 2023
Accepted: 14 December 2023
Available online: 18 December 2023

Keywords:

Nano Refrigerants
Ecofriendly refrigerants,
performance evaluation
Energy-Exergy analysis

Abstract

A fluid or liquid containing nanoparticles—particles smaller than a nanometer—is called a nanofluid. Comparably, a refrigerant with nanoparticles in it is called a nano refrigerant. These refrigerants consist of colloidal suspensions or nanoparticle mixtures created within a primary refrigerant. Carbon nanotubes, carbides, oxides, and metals are the most common materials for nano-refrigerant nanoparticles. The features of the refrigerant suspension of nanoparticles have proven to be unexpected, and their thermal qualities present an unparalleled opportunity for a wide range of applications. This work covers current and future applications in various domains, including mechanical, energy, and biomedical. It represents a theoretical investigation of nano refrigerants' thermal characteristics concerning nanoparticle size and concentration. Finally, the report highlights the directions in which future HFO-based research on the thermal performances of VCRS can go.

1. Introduction

Nanoparticles and nanoparticle-based devices have gained significant interest in various industrial applications due to their unique and advantageous properties. The high surface-to-volume ratio and size effects of nanoparticles introduce size-dependent phenomena, including chemical, electronic, magnetic, and mechanical properties. In the field of nanotechnology, particles are defined as small objects that behave as a whole unit concerning their transport and properties. They are classified based on their diameter, with coarse particles ranging from 10,000 to 2,500 nanometers, fine particles sized between 2,500 and 100 nanometers, and ultrafine particles or nanoparticles ranging from 1 to 100 nanometers [1]. Nanoparticles may exhibit size-related properties that differ significantly from those observed in fine particles or bulk materials. However, not all molecules are considered nanoparticles, as individual molecules typically do not fall within the defined size range. Nano powders are agglomerates of ultrafine particles, nanoparticles, or nanoclusters. Nanometer-sized single crystals, also known as nanocrystals, are often referred to as single-domain ultrafine particles. Nanoparticles have also found applications in the field of refrigeration, contributing to advancements in efficiency, heat transfer, and refrigerant performance. The use of nanoparticles in refrigeration systems is a relatively recent development. The introduction of nanoparticles in refrigeration systems stems from the desire to enhance the heat transfer properties of refrigerants and improve system performance. By incorporating nanoparticles into refrigerants or refrigerant oils, researchers aim to overcome challenges and limitations associated with traditional refrigeration systems [2].

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https://doi.org/10.36037/IJREI.2024.8101

2. Properties of nanoparticles [3]

Nanoparticles exhibit a range of unique properties that differ from those of bulk materials or larger particles. These properties are a result of their small size, large surface area-to-volume ratio, and quantum effects. Here are some key properties of nanoparticles:

(i) Size-dependent Properties

The properties of nanoparticles can vary based on their size. As the size decreases to the nanoscale, quantum effects become more prominent, leading to changes in electronic, optical, and magnetic properties. For example, the bandgap of semiconductor nanoparticles can be tuned by controlling their size, resulting in different optical properties.

(ii) Large Surface Area

Nanoparticles possess a significantly larger surface area compared to their volume. This increased surface area enhances their reactivity, making them highly effective in catalytic reactions. The high surface-to-volume ratio also allows for efficient interactions with other materials, such as gases, liquids, and biological systems.

(iii) Enhanced Reactivity

Due to their small size and increased surface area, nanoparticles exhibit enhanced reactivity. This property is particularly beneficial in applications such as catalysis, where nanoparticles can act as highly efficient catalysts, promoting chemical reactions with lower energy requirements.

(iv) Mechanical Properties

Nanoparticles can have improved mechanical properties compared to bulk materials. Their small size allows for the formation of unique crystal structures and increased strength. These properties make nanoparticles valuable in materials science for developing high-strength materials, coatings, and composites.

(v) Optical Properties

Nanoparticles can exhibit size-dependent optical properties. For example, metal nanoparticles can exhibit plasmonic effects, where the collective oscillation of electrons leads to enhanced absorption and scattering of light. This property is utilized in applications such as sensors, imaging, and optoelectronics.

(vi) Magnetic Properties

Certain nanoparticles, such as magnetic nanoparticles, exhibit unique magnetic properties. Their small size allows for improved control over magnetic behavior, enabling applications in data storage, magnetic resonance imaging (MRI), and magnetic separation techniques.

(vii) Surface Effects

The surface of nanoparticles plays a crucial role in their behavior and interactions. Surface chemistry, charge, and composition can significantly influence their reactivity, stability, and interactions with other molecules or materials. Surface modifications and functionalization are often performed to tailor the properties and enhance the performance of nanoparticles. It's important to note that the properties of nanoparticles can be influenced by factors such as composition, shape, surface coatings, and environmental conditions.

2.1 Preparation of Nano-refrigerants [3]

Nano-refrigerants are prepared by suspending a small quantity of nanoparticles in a base fluid like water, ethylene glycol, etc. with or without stabilization techniques. There are two most common methods to produce nano-refrigerants.

2.1.1 Two step method

The two-step method is the simplest and most common method for the development of nanofluids. This process evolves with the means of physical or chemical processes nano sized dry powders are produced of the desired material. Then with the help of different mixing processes like homogenizing, ball milling, ultrasonic agitation, high-shear mixing, and in-tensive magnetic force agitation these dry powders are diffused in a base fluid. It is the most economical method to produce nanofluids as different industries are producing nanofluids with the same synthesis technique. Aggregation of nanoparticles is the major issue in this method due to surface activity and high surface area and due to aggregation, the nanofluids are unstable. To overcome the problem of stability in the two-step method new and advanced techniques are in-troduced like one step method. In the next section, we will discuss on one-step method with the use of surfactants in the fluids. Surfactants are active agents when added to any fluid they in-crease the spreading and wetting properties but in high-temperature applications, the behavior of surfactants is still an issue.

2.1.2 One step method

Eastman et al. [4] introduced a one-step method named-physical vapor condensation process to eliminate the problem of aggregation of nanoparticles in the fluid and prepared nanofluid of copper nanoparticles suspended in the solution of ethylene glycol. The process of manufacturing and suspension of nanoparticles is done simultaneously at the same time in this method. In this method, the fluid is very stable and agglomeration is very low due to the absence of processes like depositary, conveyance, drying, and suspension of nanoparticles in the fluid. Nanofluids with a uniform dispersion of nanoparticles and a high level of stability can be achieved by the one-step method. For different dielectric liquids, a vacuum-based process named submerged arc nanoparticle synthesis system is used to prepare stable nanofluids. The thermal conductivity of the dielectric liquid can predict the behavior of the nanofluid at different operating conditions. Several investigations are done and found that due to undesired aggregation nanoparticles create different undesirable structures of the square, polygon, circular and needle-like structures. The one-step method is the most suitable method to eliminate the problem of aggregation. The one-step chemical method is the most useful method due to its cheap operation and large-scale production as compared to the one-step physical method.

3. Copper oxide (CuO) nanoparticles [5]

Copper oxide (CuO) nanoparticles are a type of nanomaterial that consists of copper and oxygen atoms arranged in a crystalline structure at the nanoscale. These nanoparticles exhibit unique properties and have garnered significant attention due to their various potential applications. Here are some key aspects related to copper oxide nanoparticles:

(i) Synthesis

Copper oxide nanoparticles can be synthesized using several methods, including chemical precipitation, thermal decomposition, sol-gel synthesis, hydrothermal methods, and green synthesis approaches. The choice of synthesis method influences the size, shape, and surface properties of the nanoparticles.

(ii) Size and Shape

Copper oxide nanoparticles typically range in size from a few to several tens of nanometers, with a high aspect ratio. The shape can vary, including spherical, rod-like, or more complex morphologies. The size and shape of the nanoparticles can impact their physicochemical properties and performance in different applications.

(iii) Optical Properties

CuO nanoparticles exhibit interesting optical properties. They possess a wide bandgap, resulting in absorption in the ultraviolet (UV) region and weak visible light absorption. These properties make them potentially useful in applications such as photocatalysis, solar cells, and sensors.

(iv) Electrical and Magnetic Properties

Copper oxide nanoparticles demonstrate semiconducting behavior, with electrical conductivity that can be tuned by controlling their size and doping. They also exhibit weak ferromagnetism at low temperatures. These properties make CuO nanoparticles relevant for applications in electronic devices, sensors, and spintronics.

(v) Catalytic Activity

Copper oxide nanoparticles have shown promising catalytic activity in various chemical reactions. They can act as catalysts or catalyst supports in processes such as oxidation, reduction, and gas sensing. Their high surface area and unique surface chemistry contribute to their catalytic efficiency.

(vi) Antibacterial Properties

CuO nanoparticles possess antimicrobial properties, making them suitable for applications in biomedical fields, such as antibacterial coatings, wound dressings, and water disinfection. The nanoparticles can interact with bacterial cells, leading to cell damage and inhibition of bacterial growth.

(vii) Energy Storage

CuO nanoparticles have been investigated for their potential in energy storage applications. They can be used as electrode materials in lithium-ion batteries, supercapacitors, and solar energy conversion devices, due to their high capacity, fast charge-discharge rates, and stability.

(viii) Environmental Applications

Copper oxide nanoparticles have been explored for environmental remediation applications. They can be utilized in the removal of pollutants from water and air, such as organic dyes, heavy metals, and volatile organic compounds (VOCs), due to their adsorption and catalytic properties.

3.1 Copper oxide nanoparticles chemical properties [6]

Copper oxide (CuO) nanoparticles possess distinct chemical properties that arise from the interaction of copper and oxygen atoms at the nanoscale. Here are some key chemical properties of CuO nanoparticles:

(i) Oxidation State

Copper oxide nanoparticles consist of copper ions (Cu2+) and oxide ions (O2-). The copper ion is in the +2 oxidation state, while oxygen is in the -2 oxidation state. The presence of these oxidation states affects the reactivity and chemical behavior of CuO nanoparticles.

(ii) Stability

CuO nanoparticles exhibit good chemical stability under normal conditions. They are relatively resistant to oxidation and can withstand moderate temperatures. However, the stability can be influenced by the surrounding environment, such as pH, temperature, and exposure to reactive species.

(iii) Redox Activity

Copper oxide nanoparticles possess redox activity, meaning they can undergo reduction and oxidation reactions. Copper ions within the nanoparticles can alternate between the +2 and +1 oxidation states, leading to redox processes. This property makes CuO nanoparticles useful in catalytic and electrochemical applications.

(iv) Acid-Base Properties

CuO nanoparticles are basic in nature. They can react with acids to form copper salts and water. The basicity arises from the presence of oxide ions on the nanoparticle surface, which can accept protons from acids.

(v) Surface Chemistry

The surface of CuO nanoparticles plays a crucial role in their chemical properties. The high surface area-to-volume ratio of nanoparticles results in a large number of exposed atoms and dangling bonds on the surface. These surface sites can interact with other molecules, facilitating adsorption, catalysis, and chemical reactions.

(vi) Reactivity

CuO nanoparticles are reactive materials due to their small size and high surface area. They can participate in various chemical reactions, including oxidation, reduction, and gas-phase reactions. Their reactivity can be harnessed for applications such as catalysis, gas sensing, and energy storage.

(vii) Interaction with Other Substances

CuO nanoparticles can interact with different substances, such as gases, liquids, and other solid materials. They can adsorb molecules onto their surface, form complexes with ligands, and undergo chemical transformations in the presence of specific reactants.

(viii) Corrosion Resistance

Copper oxide nanoparticles exhibit corrosion resistance due to the formation of a protective oxide layer on their surface. This oxide layer prevents further oxidation of the copper core and inhibits corrosion processes. It is important to note that the chemical properties of CuO nanoparticles can be influenced by factors such as nanoparticle size, surface modifications, and surrounding environmental conditions.

3.2 Copper oxide (CuO) nanoparticles Applications [5,10]

Copper oxide (CuO) nanoparticles have garnered significant attention across various fields due to their unique properties, leading to diverse applications. In electronics, CuO nanoparticles find utility in developing conductive inks and transparent conductive films, contributing to the manufacturing of flexible and efficient electronic devices. The antimicrobial properties of CuO nanoparticles make them valuable in the medical field, particularly for wound healing and as antibacterial agents in healthcare products. In energy storage systems, CuO nanoparticles enhance lithium-ion batteries' performance, showing promise for next-generation energy storage technologies. The catalytic properties of CuO nanoparticles find applications in environmental remediation, aiding in the degradation of pollutants and wastewater treatment. Additionally, in the field of sensors, CuO nanoparticles demonstrate sensitivity to various gases, making them suitable for gas-sensing applications in environmental monitoring and industrial safety. The versatility of CuO nanoparticles extends to the realm of catalysis, where they are utilized in organic synthesis reactions, showcasing their potential in the pharmaceutical and chemical industries. Overall, the multifaceted applications of CuO nanoparticles underscore their significance in advancing technology, healthcare, energy, and environmental sectors.

4. Titanium Oxide (TiO2) nanoparticles [6-9]

Titanium oxide (TiO2) nanoparticles have emerged as a versatile nanomaterial with many applications across diverse fields. Synthesized through methods such as sol-gel synthesis, hydrothermal synthesis, and chemical vapor deposition, the size and shape of these nanoparticles can be precisely controlled, influencing their properties. Ranging from a few to several tens of nanometers, TiO2 nanoparticles come in various shapes like spherical, rod-like, or more complex morphologies, impacting their functionalities. Their exceptional photocatalytic properties make TiO2 nanoparticles invaluable in photocatalysis applications. They absorb UV light, generating electron-hole pairs, enabling applications in water purification, air pollution control, self-cleaning surfaces, and degradation of organic pollutants. Additionally, their intriguing optical properties, characterized by a wide bandgap, render them suitable for UV-blocking coatings, sunscreens, and optical devices. With a large surface area-to-volume ratio, TiO2 nanoparticles find applications in gas sensors, catalyst supports, and energy storage devices. Biomedical applications include drug delivery systems, bioimaging, and photodynamic therapy, owing to their biocompatibility and controlled release properties. The nanoparticles exhibit antibacterial and antimicrobial properties, inhibiting the growth of bacteria, viruses, and fungi, making them applicable in water treatment, antimicrobial coatings, and medical devices. TiO2 nanoparticles showcase promise in energy storage as electrode materials in lithium-ion batteries, supercapacitors, and dye-sensitized solar cells. Their unique electrochemical properties contribute to enhanced energy storage capabilities. Transparent conductive films incorporating TiO2 nanoparticles are employed in optoelectronics, touchscreens, and solar cells.

Furthermore, TiO2 nanoparticles play a crucial role in environmental remediation, adsorbing or photocatalytically degrading pollutants in water and air. Continued research aims to explore additional applications and optimize TiO2 nanoparticle performance, underscoring their ongoing significance in advancing technology, medicine, energy, and environmental sustainability.

4.1 Titanium Oxide (TiO2) nanoparticles chemical properties [6-9]

Titanium oxide (TiO2) nanoparticles boast many chemical properties derived from their composition and structure, underscoring their versatility across various applications. Firstly, TiO2 nanoparticles exhibit remarkable chemical stability, rendering them resistant to corrosion and degradation in diverse environments, ensuring their prolonged use without significant compositional changes. Titanium, primarily in the +4 oxidation state (Ti(IV)), imparts chemical reactivity and photocatalytic prowess to TiO2 nanoparticles. Their photocatalytic activity is particularly noteworthy, triggered by ultraviolet (UV) light exposure, leading to the generation of electron-hole pairs. These pairs engage in redox reactions, facilitating organic pollutants' degradation and converting harmful compounds into less toxic forms. Additionally, TiO2 nanoparticles display amphoteric behavior, acting as both acids and bases. Their surface can release or accept protons in acidic or basic conditions, a crucial aspect for catalytic and surface chemical reactions. Surface functionalization allows modification through chemical attachments, tailoring properties, and enhancing interactions with other substances. TiO2 nanoparticles actively engage in redox reactions, which are crucial for their catalytic activity and the oxidation or reduction of specific compounds. Their high surface area facilitates substantial adsorption capacity, accommodating various substances like organic molecules, heavy metals, and pollutants. Notably hydrophilic, TiO2 nanoparticles readily disperse in aqueous solutions, making them valuable in water treatment and environmental remediation. The sensitivity to pH underscores their adaptability to environmental conditions, influencing surface charge, reactivity, and interactions. Furthermore, their photo-reactivity enables chemical property modulation under UV irradiation, leading to photo-redox reactions and generating reactive oxygen species.

4.2 Physical properties of TiO_2 [3,6-9]

Titanium oxide (TiO2) nanoparticles encompass a spectrum of physical attributes intricately tied to their dimensions, structure, and shape. Ranging from 1 to 100 nanometers, their petite size imparts an expansive surface area-to-volume ratio, influencing reactivity, adsorption capacity, and optical features. Existing predominantly in anatase, rutile, and brookite crystal structures, the crystal lattice affects optical, electrical, and mechanical characteristics. Their minuscule dimensions contribute to a heightened surface area, fostering increased interaction with gases, liquids, and solids, amplifying catalytic activity and adsorption capabilities. Noteworthy optical properties arise from a wide bandgap, rendering them transparent in the visible spectrum, and this can be fine-tuned by manipulating size and shape, rendering TiO2 nanoparticles valuable in UV absorption applications like sunscreens and optical coatings. Renowned for their photocatalytic prowess, exposure to ultraviolet (UV) light prompts the generation of electron-hole pairs, initiating redox reactions and making TiO2 nanoparticles invaluable in water purification, air pollution control, and self-cleaning surfaces. Exceptional thermal stability allows these nanoparticles to endure elevated temperatures without substantial structural or chemical alterations, making them apt for high-temperature applications. While exhibiting typically low electrical conductivity, doping or structural adjustments modifications render TiO2 nanoparticles suitable for applications in sensors, electronic devices, and energy storage systems. Enhanced mechanical properties, including increased strength, hardness, and flexibility, make them favorable for durable applications. Although inherently lacking magnetic properties, controlled doping or surface modifications can confer magnetism, finding utility in data storage, magnetic resonance imaging (MRI), and magnetic separation techniques. Acknowledging their propensity to agglomerate due to antiparticle forces, proper surface modifications or dispersing agents become imperative for achieving uniform dispersion in solvents or matrices. These diverse physical properties collectively position TiO2 nanoparticles as versatile entities, finding applications across photo-catalysis, optoelectronics, energy storage, sensors, coatings, and biomedical devices. The mastery and comprehension of these physical characteristics open avenues for optimizing TiO2 nanoparticles in specific applications, paving the way for continual research and development.

5. Results and Discussion

Thermal performances of VCRS using HFCO refrigerants in the primary circuit have been investigated and results have been presented in the tables -1 to table-2 respectively.

Table-1(a): Evaluation of thermal design performance parameters of VCR system using HCFO-1233zd(E) refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HCFO-1233zd(E)	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.33	2.895	15.7
2	Exergy Efficiency	0.346	0.2887	19.7
3	$U_{\_Eva}$ (W/m^{2o}C)	1095.5	655.7	67.0
4	$U_{\_Cond}$ (W/m^{2o}C)	675.7	623.5	8.37

Table-1(a) to table-1(c) showed the evaluation of thermal design performance parameters of VCR system using HCFO-1233zd(E) refrigerants in primary circuit and glycol based three nano fluids in secondary fluid circuit of evaporator and It has been observed that glycol based fluid is mainly utilized in the secondary circuit of the evaporator gives lower thermal performances than using Brine fluid flow secondary circuit of evaporator. The first law tand second law thermal performances using copper oxide is better than using Al_2O_3 and TiO_2 nano fluid.

Table-1(b): Evaluation of thermal design performance parameters of VCR system using HCFO-1233zd(E) refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HCFO-1233zd(E)	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.26	2.895	12.57
2	Exergy Efficiency	0.333	0.2887	15.257
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1072.25	655.7	63.527
4	$U_{\_Cond}$ ($W/m^{2o}C$)	663.109	623.5	6.353

Table-1(c): Evaluation of thermal design performance parameters of VCR system using HCFO-1233zd(E) refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HCFO-1233zd(E)	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.19	2.895	10.257
2	Exergy Efficiency	0.33	0.2887	11.527
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1046.0	655.7	59.527
4	$U_{\_Cond}$ ($W/m^{2o}C$)	650.65	623.5	4.353

Table-2(a) to table-2(c) showed the evaluation of thermal design performance parameters of VCR system using HCFO-low GWP 1224yd(Z) refrigerants in primary circuit and glycol based three nano fluids in secondary fluid circuit of evaporator and It has been observed that glycol based fluid is mainly utilized in the secondary circuit of the evaporator gives lower thermal performances than using Brine fluid flow secondary circuit of evaporator. The first law tand second law thermal performances using copper oxide is better than using Al_2O_3 and TiO_2 nano fluid. Among the eco-friendly refrigerants studied, in tables-1 and tables-2 HCFO1223zd(E). showed superior COP under comparable operating conditions R1224yd(Z).

Table-2(a): Evaluation of thermal design performance parameters of VCR system using HCFO-1224yd(Z)refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator

S. N	Performance Parameters for HCFO-1224yd(Z)	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.32	2.88	15.08
2	Exergy Efficiency	0.3420	0.2880	18.87
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1075.5	650.7	65.2
4	$U_{\_Cond}$ ($W/m^{2o}C$)	670.5	620.9	8.06

Thermal performances of VCRS using HFCO refrigerants in the primary circuit have been investigated and results have been presented in the tables -3 to tables-8 respectively.
Furthermore, in the primary circuit, employing HFO1336mzz(Z) in the evaporator leads to enhanced performance compared to R1243zf, R1234yf, R1225ye(Z), and R-134a. Although slightly inferior performances as compared to HCFO-1233zd(E).

Table-2(b): Evaluation of thermal design performance parameters of VCR system using HCFO-1224yd(Z)refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator

S. N	Performance Parameters for HCFO-1224yd(Z)	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.240	2.88	12.527
2	Exergy Efficiency	0.328	0.288	16.253
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1049.271	650.7	61.253
4	$U_{\_Cond}$ ($W/m^{2o}C$)	658.68	620.9	6.153

Table-2(c): Evaluation of thermal design performance parameters of VCR system using HCFO-1224yd(Z)refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HCFO-1224yd(Z)	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.154	2.88	9.526
2	Exergy Efficiency	0.31954	0.2880	10.953
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1016.74	650.7	56.253
4	$U_{\_Cond}$ ($W/m^{2o}C$)	646.89	620.9	4.253

5.1 Thermal Performances of VCRS using nano fluid in secondary circuit and HFO refrigerants in the primary circuit.

The introduction of low GWP refrigerants with R-178 in the secondary circuit of the evaporator resulted in apparent variations in COPs, both in terms of improvement and decrement. Incorporating nanomaterials with HFO-1336mzz(Z) as substitutes for R134a yields notable enhancements in second law efficiency, with improvements of 14.45% using CuO, 12.76% Al_2O_3, and 9.76% using TiO_2, respectively. As shown in Table-3(a) to Table-3(c) respectively. Similarly, exergy efficiency is also improved by using nano materials in the glycol-based fluid in the secondary fluid as 17.7% using CuO, 15.76% Al_2O_3, and 9.76% using TiO_2, respectively. Similarly overall heat transfer coefficient of evaporator was enhanced from 64.3% using CuO, 61.95% Al_2O_3, and 61.16% using TiO_2, respectively as shown in table-3(a) to tables3-(c) respectively. The compressor's isentropic efficiency is highest when using CuO and lowest with TiO_2 in conjunction with HFO1336mzz(Z). Similarly, the compressor's volumetric efficiency follows the same trend, being highest with CuO and lowest with TiO_2 in combination with HFO1336mzz(Z). The integration of nanomaterials, specifically CuO, Al_2O_3, and TiO_2, leads to significant improvements in first law efficiency, registering increments of approximately 18.5%, 17.5%, and 15.95%, respectively. The use of CuO, Al_2O_3, and TiO_2 for condenser tube enhancements also results in variations in exergetic efficiency, with improvements of about 7.1855%, 5.97%, and 4.95%, respectively. Additionally, the overall evaporator heat transfer coefficient is highest when utilizing CuO and lowest with TiO_2in combination with HFO1336mzz(Z).

Table-3(a): Evaluation of thermal design performance parameters of VCR system using HFO-1336mzz(Z) refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1336mzz(Z)	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.3	2.875	14.45
2	Exergy Efficiency	0.3387	0.2878	17.7
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1065.0	648.4	64.28
4	$U_{\_Cond}$ ($W/m^{2o}C$)	663.8	619.3	7.1855

Table-3(b): Evaluation of thermal design performance parameters of VCR system using HFO-1336mzz(Z) refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1336mzz(Z)	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.24	2.875	12.76
2	Exergy Efficiency	0.333	0.2878	15.76
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1050.15	648.4	61.95
4	$U_{\_Cond}$ ($W/m^{2o}C$)	656.27	619.3	5.97

Table-3(c): Evaluation of thermal design performance parameters of VCR system using HFO-1336mzz(Z) refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1336mzz(Z)	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.16	2.875	9.8
2	Exergy Efficiency	0.316	0.2878	9.77
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1048.8	648.4	61.07
4	$U_{\_Cond}$ ($W/m^{2o}C$)	645.28	619.3	4.95

The COPs (COP), both in terms of improvement and decrement. Incorporating nanomaterials with HFO- 1243zf as substitutes for R134a yields notable enhancements in second law efficiency, with improvements of 13.65% using CuO, 11.7% Al_2O_3, and 9.7% using TiO_2, respectively shown in Table-4(a) to Table-4(c) respectively. Similarly, exergy efficiency is also improved by using nano materials in the glycol-based fluid in the secondary fluid as 17.7% using CuO, 15.9% Al_2O_3, and 9.62% using TiO_2, respectively. The integration of nanomaterials, specifically CuO, Al_2O_3, and TiO_2, leads to significant improvements in heat transfer rates in evaporator registering increments of approximately 64.82%, 60.96%, and 59.56%, respectively. The use of CuO, Al_2O_3, and TiO_2 for condenser tube enhancements also results in variations in exergetic efficiency, with improvements of about 8.07%, 2.69%, and 2.39%, respectively. Additionally, the overall evaporator heat transfer coefficient is highest when utilizing CuO and lowest with TiO_2in combination with HFO-1243zf.

Table-4(a): Evaluation of thermal design performance parameters of VCR system using HFO-1243zf refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator

S.N	for HFO-1243zf	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.23	2.839	13.67
2	Exergy Eff	0.3385	0.2879	17.6
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1052.7	638.7	64.82
4	$U_{\_Cond}$($W/m^{2o}C$)	633.2	613.3	8.066

Table-4(b): Evaluation of thermal design performance parameters of VCR system using HFO-1243zf refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1243zf	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.176	2.875	11.87
2	Exergy Eff	0.3337	0.2878	15.9
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1022.54	648.4	60.1
4	$U_{\_Cond}$ $W/m^{2o}C$)	629.8	619.3	2.69

Table-4(c): Evaluation of thermal design performance parameters of VCR system using HFO-1243zf refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1243zf	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.115	2.875	9.72
2	Exergy Eff	0.3156	0.2878	9.62
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1019.54	648.4	59.56
4	$U_{\_Cond}$ ($W/m^{2o}C$)	627.97	619.3	2.392

Table-5(a): Evaluation of thermal design performance parameters of VCR system using HFO-1234ze(E)refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1234ze(E)	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.23	2.839	13.7
2	Exergy Eff	0.3386	0.2879	17.6
3	$U_{\_Eva}$ ($W/m^{2o}C$)	1052.7	638.3	64.83
4	$U_{\_Cond}$ ($W/m^{2o}C$)	663.3	613.3	8.153

The improvement in COP, of VCRS by Incorporating nanomaterials with HFO-1234ze(E) as substitutes for R134a yields notable enhancements in second law efficiency, with improvements of 13.7% using CuO, 11.9% Al_2O_3, and 9.79% using TiO_2, respectively shown in Table-5(a) to Table-5(c) respectively. Similarly, exergy efficiency is also improved by using nano materials in the glycol-based fluid in the secondary fluid as 17.6% using CuO, 15.94% Al_2O_3, and 8.26% using TiO_2, respectively. The integration of nanomaterials, specifically CuO, Al_2O_3, and TiO_2, leads to significant improvements in heat transfer rates in evaporator registering increments of approximately 64.83%, 60.37%, and 59.75%, respectively. The use of CuO, Al_2O_3, and TiO_2 for condenser tube enhancements also results in variations in exergetic efficiency, with improvements of about 8.15%, 2.9%, and 2.6%, respectively. Additionally, the overall evaporator heat transfer coefficient is highest when utilizing CuO and lowest with TiO_2in combination with HFO-1234ze(E).

Table-5(b): Evaluation of thermal design performance parameters of VCR system using HFO-1234ze(E)refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator

S.N	Performance Parameters for HFO-1234ze(E)	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.177	2.839	11.90
2	Exergy Eff	0.3338	0.2879	15.94
3	$U_{\_Eva}$ (W/m^{2o}C)	1024.3	638.3	60.37
4	$U_{\_Cond}$ (W/m^{2o}C)	631.2	613.3	2.917

Table-5(c): Evaluation of thermal design performance parameters of VCR system using HFO-1234ze(E)refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator.

S.N	Performance Parameters for HFO-1234ze(E)	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.117	2.839	9.79
2	Exergy Eff	0.3158	0.2879	8.266
3	$U_{\_Eva}$ (W/m^{2o}C)	1020.2	638.3	59.75
4	$U_{\_Cond}$ (W/m^{2o}C)	629.27	613.3	2.604

Table-6(a): Evaluation of thermal design performance parameters of VCR system using HFO-1225ye(Z) refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator.

S.N	for HFO-1225ye(Z)	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.227	2.839	13.65
2	Exergy Eff	0.3370	0.2878	17.095
3	$U_{\_Eva}$ (W/m^{2o}C)	1032.7	633.3	63.07
4	$U_{\_Cond}$ (W/m^{2o}C)	677.45	613.3	8.066

The enhancement in COP, of VCRS by Incorporating nanomaterials with HFO-1225ye(Z) as substitutes for R134a yields notable enhancements in second law efficiency, with improvements of 13.67% using CuO, 13.66% Al_2O_3, and 8.9% using TiO_2, respectively shown in Table-6(a) to Table-6(c) respectively. Similarly, exergy efficiency is also improved by using nano materials in the glycol-based fluid in the secondary fluid as 17.096% using CuO, 9.97% Al_2O_3, and 8.96% using TiO_2, respectively. The integration of nanomaterials, specifically CuO, Al_2O_3, and TiO_2, leads to significant improvements in heat transfer rates in evaporator registering increments of approximately 63.07%, 59.97%, and 58.9%, respectively. The use of CuO, Al_2O_3, and TiO_2 for condenser tube enhancements also results in variations in exergetic efficiency, with improvements of about 8.07%, 5.4%, and 3.7%, respectively. Additionally, the overall evaporator heat transfer coefficient is highest when utilizing CuO and lowest with TiO_2in combination with HFO-1225ye(Z)

Table-6(b): Evaluation of thermal design performance parameters of VCR system using HFO-1225ye(Z) refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator

S.N	for HFO-1225ye(Z)	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.1628	2.839	11.75
2	Exergy Eff	0.3165	0.2878	9.98
3	$U_{\_Eva}$ W/m^{2o}C)	1013.128	633.3	59.976
4	$U_{\_Cond}$(W/m^{2o}C)	646.45	613.3	5.405

Table-6(c): Evaluation of thermal design performance parameters of VCR system using HFO-1225ye(Z) refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator.

S.N	Performance Parameters for HFO-1225ye(Z)	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.084	2.839	8.976
2	Exergy Eff	0.3158	0.2878	9.72
3	$U_{\_Eva}$ (W/m^{2o}C)	1006.8	633.3	58.9
4	$U_{\_Cond}$ (W/m^{2o}C)	636.11	613.3	3.72

Table-7(a): Evaluation of thermal design performance parameters of VCR system using HFO-1234yf refrigerants in primary circuit and glycol based CuO nano fluid in secondary fluid circuit of evaporator.1225ye(Z)

S.N	Performance Parameters for HFO-1234yf	COP with CuO Nano	COP without Nano	% improvement
1	COP	3.128	2.837	10.257
2	Exergy Eff	0.3321	0.2874	9.55
3	$U_{\_Eva}$ (W/m^{2o}C)	1025.75	631.3	62.45
4	$U_{\_Cond}$(W/m^{2o}C)	675.45	611.3.9	10.5

Table-7(b): Evaluation of thermal design performance parameters of VCR system using HFO-1234yf refrigerants in primary circuit and glycol based Al_2O_3 nano fluid in secondary fluid circuit of evaporator.

S.N	Performance Parameters for HCFO-1234yf	COP with Al_2O_3 Nano	COP without Nano	% improvement
1	COP	3.073	2.837	8.35
2	Exergy Eff	0.306	0.2874	6.49
3	$U_{\_Eva}$ (W/m^{2o}C)	987.92	631.3	56.49
4	$U_{\_Cond}$ (W/m^{2o}C)	628.10	611.3.9	2.749

By Incorporating nanomaterials in VCRS using HFO-1234yf as substitutes for R134a yields notable enhancements in COP second law efficiency, with improvements of 10.26% using CuO, 6.49% using Al_2O_3, and 5.5% using TiO_2, respectively shown in Table-7(a) to Table-7(c) respectively. Similarly, exergy efficiency is also improved by using nano materials in the glycol-based fluid in the secondary fluid as 9.55% % using CuO, 6.49 using Al_2O_3, and 5.49% using TiO_2, respectively. The integration of nanomaterials, specifically CuO, Al_2O_3, and TiO_2, leads to significant improvements in heat transfer rates in evaporator registering increments of approximately 62.45%, 56.49%, and 54.49%, respectively. Similarly, the overall condenser heat transfer coefficient exhibits the same trend, with CuO yielding the highest coefficient and TiO yielding the lowest when paired with HFO1234yf and glycol is mostly used in the secondary circuit of the evaporator, are10.5%, 2.75%, and 2.01 %.

Table-7(c): Evaluation of thermal design performance parameters of VCR system using HFO-1234yf refrigerants in primary circuit and glycol based TiO_2 nano fluid in secondary fluid circuit of evaporator.

S.N	Performance Parameters for HCFO-1234yf	COP with TiO_2 Nano	COP without Nano	% improvement
1	COP	3.0182	2.837	6.39
2	Exergy Eff	0.3032	0.2874	5.49
3	U_{Eva} (W/m^{2o}C)	975.29	631.3	54.49
4	U_{Cond} (W/m^{2o}C)	623.6	611.3.9	2.012

6. Conclusions

The thermal performances of the VCR system with different HFO and HCFO refrigerants in the primary circuit and Gylcol based fluid in the secondary circuit of the evaporator with suspended nanoparticles in the circuit have been evaluated and it was found that three factors (mass flow rate of brine, compressor speed and water flow rate in the condenser strongly affecting system thermal performance enhancement (COP), heat transfer characteristics, and solubility of nano refrigerants into the base refrigerant . The following conclusions were drawn

- Use of nano refrigerants required lower power consumption however by using nano refrigerants in secondary circuit increases the evaporator and condenser heat transfer rates in VCR systems.
- Using CuO nano refrigerants maximizing the improvement in the heat transfer coefficient of thermal evaporators.
- The system's overall coefficient of performance (COP) and freezing capacity can both be improved by including nano refrigerants. CuO and HCFO-1233zd(E) refrigerants is higher than HCFO-1224yd(Z) is used in this combination.
- When nano refrigerants are used in the system with the same input parameters as HFO refrigerants, heat transfer rates and system efficiency (first and second law) can be significantly increased utilizing R1336mzz(Z). while HFO-1234yf in the primary circuit yields the lowest performances.
- When comparing the thermal system performance under identical input settings, the brine flow nano fluid significantly outperformed the glycol-based nano fluid.

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***Cite this article as*:** R.S. Mishra, Thermophysical property of nano-refrigerant: preparation, thermal characteristics, and applications in the VCR system using HFCO and HFO refrigerants in primary circuit and glycol based nano refrigerants in secondary circuit, International Journal of Research in Engineering and Innovation Vol-8, Issue-1 (2024), 1-9.
https://doi.org/10.36037/IJREI.2024.8101.