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ORIGINAL ARTICLE

Thermodynamic (energy-exergy) performances comparison of VCRS using HFC+HFO blends in primary and nano mixed brine flow in secondary circuit evaporator

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Abstract

This research focuses on the effects of low GWP HFC and HFC+HFO blends on HFC refrigerants' first and second-law performances. It was discovered that using HFC-245fa refrigerant, thermodynamic second law (exergy) performances increased up to 31.04%, 30.27%, and 20.24%, respectively, by using CuO, Al_2O_3, and TiO_2 nanomaterials in brine water flowing. The comparison was made using low global warming potential three HFC refrigerants and three HFO+HFC mixed refrigerants in the primary circuit of evaporator and brine flow with and without nanomaterials. Similarly, by adding CuO, Al2O3, and TiO2 nanomaterials in the primary circuit, its thermodynamic first law performances using HFC+HFO blended refrigerant exergy performances improved up to 25.6%, 22.4%, and 20.24%, respectively.

1. Introduction

A refrigerant is a heat-carrying substance in a refrigeration system that transfers heat from a low-temperature system during VCRS. It expels heat so that a system with a greater temperature can absorb it. The first refrigerant used was a blend of salt and natural ice. Ammonia, sulfate of sulfur, methyl chloride, and carbon dioxide were the refrigerants utilized in VCRS in 1834. Methane (CH4) and ethane (C2H6) chloro-fluoro derivatives are the most widely utilized halo-carbon or organic refrigerants. Chloro-fluoro-carbon (CFC) refrigerants are completely halogenated refrigerants that contain chlorine (Cl) atoms in their molecules. These CFC refrigerants include R11, R12, R13, R113, R114, and R115. The term "hydro-chloro-fluorocarbon" (HCFC) refrigerants" refers to gases that have hydrogen (H) atoms in their molecules. HCFC refrigerants include those found in R22 and R123. HFC refrigerants are defined as refrigerants without chlorine atoms in their molecules. HFC refrigerants include R134a and R152a, among others. "hydrocarbon (HC) refrigerants" refers to refrigerants without chlorine or fluorine atoms in their molecules. These are HC refrigerants, including R290, R600a, and others. The fluorine (F) atom in the molecules of the refrigerants was discovered to make them physiologically more advantageous. The loss of this layer in the upper atmosphere, which allows dangerous UV radiation from the sun to enter the atmosphere and reach the earth's surface, is thought to be caused by the chlorine (Cl) atom in the molecules of refrigerants. The chloro-fluoro-carbon (CFC) refrigerants have been linked to the depletion of this ozone layer. They have varying degrees of ozone depletion potential (ODP). In addition to the ozone depletion effect on the

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environment, the halo-carbon refrigerants have a global warming effect, which may cause serious environmental changes. According to an international agreement, Montrel Protocol-1987, halogenated chloro-fluoro-carbon (CFC) refrigerants considered to have high ozone depletion potential ozone depletion, such as R11, R12, R13, R113, R114, R502, have been phased out. The refrigerant R22, a hydro-chloro-fluoro-carbon (HCFC) refrigerant, is not covered under the original Montreal Protocol as its ODP is one-twentieth of R11 & R12. But because of its GWP, it has to be phased out. Nevertheless, R22 is found to be of greater use these days as it is employed not only in its existing R22 applications but also as a substitute for R11 in extensive capacity air conditioning applications with screw or centrifugal compressors. Hydrocarbon (HC)& hydro-fluoro-carbon(HFC) refrigerants provide an alternative to fully halogenated chloro-fluoro-carbon (CFC) refrigerants. Since they contain no chlorine atoms at all, therefore, they have the lowest ODP. Refrigerants. Even hydro-chloro-fluoro-carbon (HCFC) refrigerants, which include some chlorine (Cl) atoms but in association with hydrogen (H) atoms, have much reduced ODP; however, the hydro-fluoro-carbons (HFCs), because of their hydrogen (H) content, may be slightly flammable. The degree of flammability depends upon the number of H atoms in the molecules. Pure hydrocarbon (HCs) are, of course, highly flammable.

1.1 Substitutes for chloro-fluoro-carbon (CFC) refrigerants

Currently, the following substitutes are available for replacement. CFC refrigerants

- The HCFC refrigerant R123 (CF_3CHCl_2) in place of R11 (CCl_3F).
- The HFC refrigerant R134a (CF_3CH_2F) & R152a (CH_3CHF_2) in place of R12.
- The HFC refrigerant R143a (CH_3CF_3) & R125 ($CHF_2 CF_3$) in place of R502 (a mixture of R22 & R115)
- The HC refrigerants, propane (R290), C_3H_8 and R600a (C_4H_{10}) may also be used in place of R12.

1.2 HFO+HFC blend as a substitute for chloro-fluoro-carbon (HFC) refrigerants

Accordingly, HFCs that do not destroy the ozone layer was developed to replace HCFCs. In Japan, companies first replaced CFC refrigerants with HCFC refrigerants and then later on with HFC refrigerants in consideration of the environment, ahead of other countries, earlier than the regulation timetable set up in the Montreal Protocol.

HFC refrigerants do not destroy the ozone layer and are non-flammable and low-toxic, which makes HFC safe and reliable. But the GWP of HFC is high. Therefore, a new movement was started to implement legal regulations on HFCs. In 2006, the EU F-gas Regulation was established first, and then the proposal to phase down HFCs under the Montreal Protocol on substances that deplete the ozone layer was issued through the leadership of the U.S. These new endeavors led to the amendment of the "Law Concerning the Recovery and Destruction of Fluorocarbons" to the "Act on Rational Use and Proper Management of Fluorocarbons" (commonly known as "Fluorocarbon Emission Control Law") and came into effect from April 2015, in Japan. As for the global scene, the Parties to the Montreal Protocol reached an agreement at their 28th Meeting of the Parties (MOP-28) in October 2016 in Kigali, Rwanda, to phase down HFCs (Kigali Amendment) [2]. It was decided that the developed countries should gradually reduce their production and consumption of HFCs (on a CO_2 equivalent basis) by 10% by 2019, by 40% by 2024, and then by 70% by 2029, and eventually by 85% by 2036.

On the other hand, developing countries would have to reduce HFC production and consumption with a time delay of approximately 10 to 13 years. As a whole, all parties are required to minimize HFCs over 30 years. This transition mechanism is similar to past efforts toward reducing HCFCs.

As a consequence of the Kigali Amendment, Japan's Fluorocarbon Emission Control Law regulations have been gradually strengthened further). In December 2017, the government announced proposals to add a centrifugal chiller to the designated product category, which demands that equipment manufacturers replace existing refrigerants with lower GWP refrigerants. Centrifugal chiller manufacturers must regulate GWP values to 100 or less from 2025 onwards. The properties of refrigerants change inevitably to achieve low-GWP levels. Although substances called natural refrigerants have a very low GWP, they have downsides too. For example, hydrocarbons are highly flammable, whereas ammonia is both high and toxic. Hydro-fluoro olefins (HFOs) with a carbon-carbon double bond have been developed recently as another candidate for a low-GWP refrigerant. HFOs decompose when exposed to ultraviolet rays and thus have a short atmospheric lifetime and a low GWP. As an inherent trade-off for reducing GWP, however, substances tend to become flammable because molecules' stability is reduced to increase the speed of decomposition. Although different types of low GWP refrigerants have been developed for various refrigeration and air-conditioning equipment, non-flammability is not necessarily-achieved property in the effort to achieve low GWP. But in many applications like large hotels, food storage and processing plants, food items are stored in different compartments and at different temperatures. The systems under vapor compression technology consume an enormous amount of electricity; this problem can be solved by improving the system's performance.

2. Use of Nano refrigerants in VCRS

Nano refrigerant fluid is used in refrigeration systems where suspended nanoparticles are well-dispersed in a continuous base refrigerant. It has a long history that has contributed to developing and enhancing modern refrigeration systems due to enhanced thermodynamic energy and exergy performances.

Many essential research investigations have been conducted on studying the thermal conductivity of water-based nano-fluids and nano-refrigerants. The thermal conductivity of CNT-based nano-refrigerants is enhanced compared to the base refrigerants fluid [1]. K. Henderson et al., [2] also performed an R-134a-CuO combination in the same horizontal tubes with POE as a lubricant and observed 100 % enhancement in heat transfer coefficient.

Adrián Mota-Babiloni [3] carried out an analysis of the feasibility of R454C and R455A, two new low global warming potential (GWP of 148) refrigerants, in VCRS as alternatives to R404A for warm countries and found that the R454C and R455A will be the most viable low GWP options to perform a direct replacement of R404A due to similar uniqueness and found experimental results show that the cooling capacity of the reserves is slightly lower than R404A, being the Coefficient of Performance (COP) of the new mixtures 10–15% higher than that of R404A, especially at more increased condensation.

Mishra [4] pointed out that the conductivity ratio of pure refrigerant to nano refrigerant increases with the concentration of nanoparticles in the host refrigerant. In contrast, Cu nanoparticle-based nano refrigerants have a higher conductivity ratio than other nanoparticles and have approx. Two times higher than base refrigerant at 5 vol % concentration and the eco-friendly HFC-134a with copper oxide as nanoparticle have the highest Effectiveness factor approx. 3.2 at 5 vol %. The effectiveness factor increases with an increasing percentage of volume (vol %), and the copper nanoparticle-based nano refrigerant has the highest convective heat transfer coefficient ratio than other nanoparticles mixed in brine water in the secondary circuit of the evaporator. In response to various environmental conventions, more environmentally friendly refrigeration systems have been investigated in recent years. Two aspects are of particular concern: ecological (ecologically friendly) refrigerants and energy consumption.

2.1 Thermodynamic analysis of VCRS

Technology is based on the rejection of heat to the surrounding at higher temperatures and absorption of heat at low temperatures; the evaporator, expansion valve, condenser and compressor are the four main components of the single-stage vapor compression system. VCRS consumes a large amount of electricity. This difficulty can be removed by improving the performance parameters of the system. Therefore, the following can enhance the thermodynamic performances of techniques based on VCRS. First-law efficiency (COP) and second-law performance (exergy efficiency) are the two main parameters used to calculate the performance of refrigeration systems.

The COP can be enhanced by minimizing the compressor's power consumption or increasing the refrigeration effect. The adoption of multi-stage throttling can increase the refrigeration effect. On the other hand, compressor power consumption can be enhanced by incorporating multi-stage compression and a flash chamber. The collective impact of these two factors improves the overall performance of the vapor compression system.

It is presented that system components' Irreversibility occurs due to significant temperature differences between the system and its surrounding. Irreversibility should be measured in the cycle to improve the system performance because exergy losses are responsible for the degradation of system performance. The Coefficient of arrangement is commonly used to calculate the performance of vapor compression systems, but COP provides no information regarding thermodynamic losses in the system components; one can quantify the exergy losses in VCRS using exergy analysis. Exergy losses increase with increasing the temperature difference between systems and surroundings. Exergy is the available or valuable energy; loss of energy means the loss of exergy in the system. Exergy losses are helpful in improving the performance of the system and better utilization of energy input given to the system, which is beneficial for environmental conditions and the economics of energy technologies. The utilization of green energy can be increased by this method. Mishra [5] computed the first and second law analysis of VCRS with and without nanoparticles using eco-friendly refrigerants (R134a, R407c, R404a, R1234yf, and R1234ze) and suggested the blends of HFOs with nanoparticles with has a promising future.

Nano refrigerants have the potential to replace R134a, and Mishra [5] found the worst thermal performance in terms of first-law efficiency, second-law efficiency and exergy efficiency. By using nano in the HFC-410a, and concluded that the best thermal performance in terms of first-law efficiency is found using R1234ze(Z). This paper mainly deals with the effect of HFC refrigerants' and HFC+HFO blended of low GWP on their first and second law performances. The Comparison has been done for using low global warming potential three HFC refrigerants and also three HFO+HFC blended refrigerants in the primary circuit of the evaporator and brine flow with nanomaterials and without nanomaterials in the secondary circuit of the evaporator using and found that by using HFC-245fa refrigerant the thermodynamic second law(exergy) performances.

3. Results and Discussion

In this paper, the following input parameters have been taken.

Table-1: Input data used in VCRS

S.No.	Description	Value with unit
1	Length of evaporator tube	7.2m
2	Length of condenser tube	12.5m
3	Mass flow rate of water flow	0.008kg/sec
4	Mass flow rate of brine flow	0.007kg/sec
5	Condenser water inlet temperature	27°C
6	Brine water inlet temperature	27°C

The thermodynamic performance of VCRS have been evaluated using low GWP HFC refrigerants in the primary circuit of the evaporator and nano mixed brine water flowing in the secondary circuit of the evaporator and thermodynamic first law (energy) performance improvement along with refrigerants are shown in Table-2(a) and second law performance using copper oxide (CuO) Nano material shown in Table-2(b) respectively.

Table-2(a) Thermodynamic first law performance (COP) of VCRS using CuO

Performance Parameters	With Nano	Without Nano	% enhancement
R245fa	3.923	2.965	31.04
R-152a	3.76	2.958	32.99
R32	3.47	2.845	34.97

Table-2(b) Thermodynamic Exergy efficiency of VCRS using CuO

Performance Parameters	With nano	Without Nano	% enhancement
R245fa	0.3925	0.2976	31.89
R-152a	0.3667	0.2935	24.940
R32	0.3526	0.2885	22.219

Table-3(a) Thermodynamic first law performance of VCRS using Al_2O_3

Performance Parameters	With Nano	Without Nano	% enhancement
R245fa	3.825	3.555	30.266
R-152a	3.656	3.376	31.639
R32	3.37	3.15	33.963

Table-3(b) Thermodynamic Exergy efficiency of VCRS using Al_2O_3

Performance Parameters	With Nano	Without Nano	% enhancement
R245fa	0.3765	0.2976	26.512
R-152a	0.3665	0.2935	24.872
R32	0.3475	0.2885	20.450

Table-4(a) Thermodynamic COP of VCRS using TiO_2

Performance Parameters	With Nano	Without Nano	% enhancement
R245fa	3.765	2.965	25.801
R-152a	3.56	2.958	20.352
R32	3.27	2.845	14.94

Table-4(b) Thermodynamic Exergy efficiency of VCRS using TiO_2

Performance Parameters	With Nano	Without Nano	% enhancement
R245fa	0.3765	0.2976	31.89
R-152a	0.3665	0.2935	24.872
R32	0.3475	0.2885	20.450

3.1 Thermodynamic performance of VCRS have been evaluated using low GWP HFC +HFO Blended refrigerants

The thermodynamic energy performance of VCRS has been evaluated using low GWP HFC refrigerants in the primary circuit of the evaporator. Nano mixed brine water was flowing in the secondary circuit of the evaporator, and thermodynamic first law performance improvement using low GWP HFC refrigerants are shown in Table-5(a) and second law performance using copper oxide (CuO) nanomaterial shown in Table-5(b) respectively.

Table-5(a) Thermodynamic first law performance (COP) of VCRS using CuO

Performance Parameters	With Nano	Without Nano	% enhancement
R 515a	3.723	2.965	25.625
R-513a	3.563	2.958	20.453
R450a	3.37	2.845	18.453

Table-5(b) Thermodynamic second law performance of VCRS using CuO

Performance Parameters	With Nano	Without Nano	% enhancement
R 515a	0.3735	0.2976	25.504
R-513a	0.3527	0.2935	20.170
R450a	0.3326	0.2885	15.286

The thermodynamic energy performance of VCRS has been evaluated using low GWP HFC refrigerants in the primary circuit of the evaporator. Nano-mixed brine water was flowing in the secondary circuit of the evaporator, and thermodynamic first law performance improvement using low GWP HFC refrigerants are shown in Table-6(a) and second law performance using Al2O3 nano material shown in Table-6(b) respectively.

Table-6(a) Thermodynamic energy performance of VCRS using Al_2O_3

Performance parameters	With Nano	Without	% enhancement
R 515a	3.629	2.965	22.395
R-513a	3.456	2.958	16.835
R450a	3.27	2.845	14.93

Table-6(b) Thermodynamic Exergy efficiency of VCRS using Al_2O_3

Performance Parameters	With Nano	Without	% enhancement
R 515a	0.3625	0.2976	21.80
R-513a	0.3435	0.2935	17.036
R450a	0.3255	0.2885	12.82

The thermodynamic energy performance of VCRS has been evaluated using low GWP HFC refrigerants in the primary circuit of the evaporator, and nano mixed brine water was flowing in the secondary circuit of the evaporator, and thermodynamic first law performance improvement using low GWP HFC refrigerants are shown in Table-7(a) and second law performance using TiO2 nano material shown in Table-7(b) respectively.

Table-7(a) Thermodynamic COP of VCRS using TiO_2

Performance Parameters	With nano	Without	% enhancement
R 515a	3.565	2.965	20.236
R-513a	3.356	2.958	13.455
R450a	3.165	2.845	7.276

Table-7(b) Thermodynamic exergy performance of VCRS using TiO_2

Performance Parameters	With Nano	Without	% enhancement
R 515a	0.3478	0.2976	16.868
R-513a	0.3367	0.2935	14.71
R450a	0.3073	0.2885	6.516

4. Conclusions

The following conclusions are made

- Thermodynamic first law (energy) performance VCRS using eco-friendly HFC refrigerants suspended with CuO, Al2O3 and TiO2 nanoparticles in the brine water of the secondary circuit of the evaporator in VCRS, it was found that the first law performance(COP) is enhanced maximum up to is about improved up to 31.04%, 30.27%, and 25.801% respectively.
- The thermodynamic second law performance of VCRS using eco-friendly HFC refrigerants suspended with CuO, Al2O3 and TiO2 nanoparticles in the brine water of the secondary circuit of the evaporator in VCRS, it was found that the first law performance(COP) is enhanced maximum up to is about improved up to 31.89 %, 26.51%, and 25.801% respectively
- The thermodynamic first law (energy) performance of VCRS by using eco-friendly blends of HFO +HFC refrigerants with suspended CuO, Al2O3 and TiO2 (titanium dioxide) nanoparticles in the brine water of the secondary circuit in the evaporator, the second law performance of the system is improved in the range of 22.4, 20.24%, 16.9%, respectively.
- The thermodynamic second law performance of VCRS using eco-friendly HFC refrigerants suspended with CuO, Al2O3 and TiO2 nanoparticles in the brine water of the secondary circuit of the evaporator in VCRS, it was found that the first law performance(COP) is enhanced maximum up to is about improved up to 25.5%, 21.8%, and 16.9% respectively. R245fa gives the best first-law thermodynamic performance (COP) and is slightly higher than HFO- 152a.
- The lower thermodynamic performances were found by using HFC-32 in the primary circuit and brine water in the secondary circuit of the evaporator of the VCRS.
- In using HFO blends, R515a gives the best first-law thermodynamic performance (COP) and is slightly higher than R513a. The lower thermodynamic performances were found by using R450a in the primary circuit and brine water in the secondary circuit of the evaporator of the VCRS.

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