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ORIGINAL ARTICLE

Energy-exergy performance evaluation of ejector coupled cascaded refrigeration systems using low GWP HFO & HCFO refrigerants for ultra-low temperature application

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Abstract

Currently, the refrigeration and air conditioning sector is looking for energy-efficient technology that can cut down on electric power use and prevent environmental harm. The ejector refrigeration system (ERS) was created to be an environmentally friendly cooling system that uses energy-efficient refrigerants. The effect of environmentally friendly refrigerants in high temperature cycles with condenser temperature at 303K and evaporator temperature at 263K and also HCFO-1233zd(E), HFO-1336mzz(Z) & HFO-1225ye(Z) used low temperature cycles with evaporator temperature at 223K to 203K along with temperature overlapping between high temperature evaporator and low temperature condenser is studied in this paper. Investigation and comparisons with various HCFO&HFO refrigerants were done to see how well ejector systems performed when it used in cascaded VCR systems for ultra-low temperature applications.

1. Introduction

With global development accelerating, energy consumption is escalating suddenly in all regions of the world. Fossil fuels are now being used much faster due to the rise in global energy consumption. These fossil fuels are not only depleting more quickly, but they are also hastening the earth's rapid warming. The refrigeration, heat pump, and air conditioning sectors need help meeting the cooling and space heating demand without contributing to global warming. Still, many refrigerators and air conditioners installed in the household and industrial sectors use the vapor compression cycle. According to predictions, the global electricity consumption for air conditioning systems using the vapor compression cycle will rise by 33% by the year 2100 as the economies of developing nations improve. To run the compressor, these devices used electricity. The Kyoto and Montreal Protocols outlawed using CFC, HCFC, and HFC. Most substitute refrigerants in residential and commercial spaces have high global warming potential (GWP). VCR Systems typically uses CFC, HFC, and HCFC refrigerants, and when these refrigerants leak from the system, they release pollutants into the environment that lower the air quality. Emissions that were produced by the system could have been direct or indirect. When refrigerants escape into the earth's atmosphere, there are direct emissions. Between 27% and 30% of hydrocarbons and hydrofluorocarbons are released into the atmosphere as leaks, while indirect emissions are by-products of the use of electricity produced from fossil fuels.

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2. Challenges of VCRS used in Refrigeration and Air conditioning

The refrigeration and air conditioning industry is searching for energy-efficient solutions to lessen electrical power usage without harming the environment. One such energy-efficient technology is the ejector refrigeration system, which can provide cooling using environmentally friendly refrigerants [1]. This technology compresses the refrigerant in the system using the energy of the primary flow. A refrigeration system's throttling device typically serves two purposes. The liquid refrigerant is growing in the thermodynamic process from the condenser pressure to the evaporator pressure. The control function is the other, and it may involve supplying the liquid to the evaporator at the pace at which it is being evaporated. Therefore, the fundamental problem in the vapor compression refrigeration cycle is the irreversibility connected to throttling. There are numerous ways to lessen the energy losses caused by throttling in refrigeration cycles. Due to its simple structure, comfortable manufacturing with no moving parts, low cost, and minimal maintenance requirements, using an ejector as an expansion device that can replace a throttling valve is a promising alternative to reduce throttling losses in terms of expansion irreversibility in the refrigeration system. Increasing the suction pressure over that of the ejector lessens the effort required of the compressor, improving the system's coefficient of performance (COP). It also makes it possible to minimize the evaporator's size by employing the energy principle [2]. Padilla et al. [3] detailed the thermodynamic study of a household VCR system employing R12 and R413A and concluded that R413A had better thermodynamic performances than R12 regarding power consumption and energy efficiency. Getu and Bansal [4] used regression analysis to optimize the cascade refrigeration system's design operating parameters, employing R717 in the high-temperature cycle and R744 in the low-temperature cycle. They then used energy and first-law analyses to evaluate the system's performance. Unable to detect system components' irreversible damage (or energy losses). To determine irreversibility regarding exergy destruction in the various components of simple and cascaded VCR systems. Due to its high GWP and negative effects on the environment, the European Union (EU) law is phasing out the current generation HFCs like R134a. Abridged use of refrigerants with high global warming potential (GWP) is required by European Parliament Directive 517/2014. Due to its high GWP and negative environmental effects, the European Union (EU) law is phasing out the current generation HFCs like R134a [5]. Mishra [6] developed an advanced approach for thermodynamic performances known as energetic analysis. Refrigerated with lower GWP must be employed in the new systems or to replace the existing HFC and HCFC refrigerants since a universal limit in the GWP can be selected at 150, especially for household refrigeration systems. The fourth-generation hydro-fluoro-olefins R1234yf and R1234ze are currently being explored as R134a substitutes. HFO-1234yf and HFO-R1234ze have been used to support numerous investigations.Studies by Mishra [7] employing R1234yf and R1234ze(E) discovered that R1234ze(Z) exhibits superior thermodynamic performance than R1234ze(E) and R1243zf. R1224yd (Z) and HFO-1336mzz(Z) exhibit thermodynamic performance that is almost the same, higher than R1234ze(E) but lower than R1224yd(Z). But R1234yf has the weakest thermodynamic properties [8]. Hydro-fluoro-olefines (HFO) and hydro-chloro-fluoro-olefines (HCFO) employed in VCR systems were examined by Mishra 2014(d,e). Particularly potential low-GWP substitutes for the HFC R134a and R245fa include the HFO R1234yf and R1234ze (E), as well as the HCFO R1233zd(E) and R1224yd(Z). For instance, the German Environment Agency proposes to forbid its application due to R1233zd(E) 's ODP of 0.00024. R1233zd(E), however, has several positive characteristics, including a very low GWP and no flammability or toxicity (safety classification of A1). This demonstrates that the extremely low ODP by R1233zd(E) and R1224yd had no discernible impact on the external costs. As a result, the data show that a blanket ban on potentially useful refrigerants with very low ODP is not warranted. Compared to R134a, utilizing HCFO-1233zd(E) requires less electrical power. Both the innovative fluids R1233zd(E) and R1224yd(Z) are suitable for the drop-in replacement of R245fa in refrigeration systems, it may be concluded [9]. The highest power output is still attained with the high-GWP fluid R245fa and R134a when R1233zd(E)is used for finding the system performances, ranging from 7% to 9%. However, the results demonstrate the compatibility of R1233zd(E) and R1224yd(Z), compared to replacement R245fa and R134a. Fuel with R245fa has an exergy of 0.40% higher than fuel with R1233zd(E) and 8% higher than fuel with R1224yd(Z). However, environmentally friendly R1233zd(E) has values roughly two percentage points greater than R245fa in terms of the Organic Rankine Cycle (ORC) system's thermodynamic efficiency. The operating conditions for the thermodynamic efficiency of HFC-245fa and R1224yd(Z) are the same and comparable. But R-1336mzz(E), also known as HFO1336mzz(Z), also offers details on the thermodynamic properties of cis-1,1,1,4,4,4-hexafluoro-2-butene (CAS-692-49-9; molecular weight: 164.056 gm/mole). These novel HFOs are being developed and have characteristics of lower GWP with ultralow ODP of a good working fluid's stability, compatibility, favorable toxicity, and performance even at high temperatures. The fundamentals of choosing a good working refrigerant are based on system optimization to optimize the first and second law efficiencies. The HFO-1336mzz(E) has a critical pressure of 3.15 MPa, a critical temperature of 137.6oC, and a boiling point of 7.5oC. However, HFO-1336mzz(Z) has a slightly higher boiling point of 33.4oC, a critical temperature of 171.3oC, and a lower critical pressure of 2.90 MPa. The condensing temperatures were modified to assess greater temperature impacts for each working fluid. The compressor efficiency, superheat, sub-cooling, and lift temperatures were fixed variables in this computation. HFO1336mzz isomers (E and Z) had good COP(COPs) compared to HFC refrigerants (such as R134a, R410a, R404a, R407c, R507a, and R125a) but were less efficient than R245fa due to the latter's 8.63% greater power consumption for operating compressors. Mishra R.S. [10,11] used a liquid-vapor heat exchanger and multiple HFO refrigerants (such as R1234yf, R1234ze(Z), R1234ze(E), R1243zf, R1224yd(z), R1225ye(z), and HFO-1336mzz(Z)) to replace R134a refrigerants in a VCR system. Of their environmental friendliness, HFO refrigerants were excellent substitutes for R134a. Pure chemicals are used in environmentally friendly refrigerants such as R134a, R1234yf, and R1234ze(E).

3. Low ozone depletion potential (ODP) and low global warming potential future refrigerants

Future refrigerants with low ozone depletion potential (ODP) and low global warming potential (GWP) will be HFO (hydro-fluoro-olefin). The fundamental characteristics of new HFO refrigerants that are anticipated to replace R134a and R32, which are now used in refrigerators. With its flammability being in the A2 category, R1243zf is certainly a good replacement for R134a.Using low GWP alternative refrigerants, Attila Gencer et al. [12] theoretically assessed the thermodynamic behaviour in terms of energy parameters (i.e., cooling capacity and COP) for three different VCR systems (i.e., basic cycle, basic cycle with liquid-to-suction heat exchanger, and two-stage cascade cycle). The energy parameters were compared for two different evaporation temperatures (-30°C and 0°C) and two different condensing temperatures (40°C and 55°C). The numerical results indicate that R450A, which almost has the same COP values as R134a, comes into prominence with a 58% lower GWP value than R134a, and that R445A gives the highest exergetic efficiency with liquid shell heat exchangers. Additionally, it was found that systems with liquid shell heat exchangers give better effects in terms of COP for the considered refrigerants and temperature cases as well as assumed system parameters. This was in line with the study's conclusions about refrigeration cycles. By comparing five low GWP refrigerants—R152a, R1234yf, R1234ze, R290, and R600a—with R134a in an experimental test rig using a hermetic compressor, Sanchez et al. [13] discovered that R1234yf is a suitable drop-in replacement for R134a when energy consumption and facility cooling refrigerating capacity are taken into account. As drop-in replacements for R134a, Mota-Babiloni, A., et al. [14,15,16] evaluated the energy performances of two low-GWP refrigerants, such as R1234yf and R1234ze(E), and carried out numerous tests in vapour compression systems by combining various values of evaporation and condensation temperature, and without/with the adoption of an internal heat exchanger. The aforementioned researchers have not assessed how well cascaded ERS with VCRS working with ultralow GWP refrigerants perform. Investigation is done into how HFO refrigerants affect the cascaded ERS system's high temperature cycle and low temperature cycle.

4. Results and Discussion

Table 1 shows the effect of high temperature cycle ecofriendly HFO refrigerants on the exergetic performances of cascaded ejector refrigeration system cascaded with vapour compression cycles HFO-1336mzz(Z)in the low temperature cycle and it was found that by using R1233zd(E) in high temperature cycle , the minimum exergy destruction ratio along with the optimum (highest value of 24.98%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 150.1%

Table 1 :Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector VCR system using HFO-1336mzz(Z) in low temperature cycle and following ecofriendly refrigerants in high temperature cycle ($T_{\_boiler}$=353(K), $T_{\_eva}$ =263(K), $T_{\_cond}$ =303(K), T_o=300(K), (L/D) =10, D_throat =0.0005 metre, D_m =0.0014 metre, D_p=0.0008metre, Diffuser angle =3° Diffuser Length ($L_{\_d}$) =(112/1000) metre, Area Ratio =7.84, Q_eva =4.75 "kW", $T_{\_eva\_LTC}$ =223(K), Ambient temperature (To) =298K)

Refrigerants in HTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrainment Ratio	Compression Ratio	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
R1234ze(Z)	0.7531	8.439	0.1059	4.796	0.7828	2.907	0.4704	3.102	0.2438
R1234ze(E)	0.7296	8.743	0.1026	3.895	0.8684	2.907	0.4580	3.030	0.2482
R1243zf)	0.7586	8.37	0.1067	3.607	0.8792	2.907	0.4733	3.054	0.2467
R1233zd(E)	0.7222	8.843	0.1016	5.146	0.7806	2.907	0.4541	3.08	0.2541
R1225ye(Z)	0.7241	8.876	0.1019	3.921	0.8692	2.907	0.4551	2.99	0.2506
R1224yd(Z)	0.7025	9.118	0.09883	4.997	0.7991	2.907	0.4436	3.03	0.2480

Table 2 shows the effect of high temperature cycle ecofriendly HFO refrigerants on the exergetic performances of cascaded ejector refrigeration system cascaded with vapour compression cycles R-1225ye(Z) in the low temperature cycle and it was found that by using R1233zd(E) in high temperature cycle ,the minimum exergy destruction ratio along with the optimum (highest value of 24.99%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 134.84% The highest second law exergetic efficiency is to be found by using HFO-1336mzz(Z) and percentage improvement is 150.1% as compared by using R1225ye(Z). Table 3 shows the effect of low temperature cycle ecofriendly HFO refrigerants on the exergetic performances of cascaded ejector refrigeration system cascaded with vapour compression cycles R-1234ze(Z**)** in the high temperature cycle and it was found that by using R1233zd(E), the minimum exergy destruction ratio along with the optimum (highest value of 24.98%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 133.05%.

Table 2: Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector VCR system using R-1225ye(Z) in low temperature cycle and following ecofriendly refrigerants in high temperature cycle(T_{boiler}=353(K), T_{eva} =263(K), T_{cond} =303(K), T_o=300(K), (L/D) =10, D_throat =0.0005 metre, D_m =0.0014 metre, D_p=0.0008metre, Diffuser angle =3^o Diffuser Length (L_d) =(112/1000) metre, Area Ratio =7.84, Q_eva =4.75 "kW", T_{eva_LTC} =223(K), Ambient temperature (To) =298K)

Refrigerants in HTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrainment Ratio	Compression Ratio	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
R1234ze(Z)	0.7531	8.439	0.1059	4.796	0.7828	2.901	0.4694	3.093	0.2443
R1234ze(E)	0.7296	8.743	0.1059	3.895	0.8684	2.901	0.4571	3.021	0.2487
R1243zf)	0.7586	8.37	0.1067	3.607	0.8792	2.901	0.4723	3.045	0.2472
R1233zd(E)	0.7222	8.843	0.1016	6.067	0.7725	2.901	0.4532	3.071	0.2457
R1224yd(Z)	0.7025	9.118	0.09883	4.997	0.7991	2.901	0.4427	3.024	0.2485
HFO-1336mzz(Z)	0.6579	9.804	0.09256	6.067	0.7725	2.901	0.4186	3.039	0.2476

Table 3 :Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector VCR system using R1234ze(Z) ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS(T_{boiler}=353(K), T_{eva} =263(K), T_{cond} =303(K), T_o=300(K), (L/D) =10, D_throat =0.0005 metre, D_m =0.0014 metre, D_p=0.0008metre, Diffuser angle =3^o Diffuser Length (L_d) =0.112 metre, Area Ratio =7.84, Q_eva =4.75 "kW", T_{eva_LTC} =223(K), Ambient temperature (To) =298K)

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrainment Ratio (shy)	Compression Ratio (mu_1)	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
HFO1336mzz(Z)	0.753	8.439	0.1059	4.796	0.7828	2.907	0.49	3.102	0.2438
R1233zd(E)	0.753	8.439	0.1059	4.796	0.7828	2.976	0.474	3.052	0.2468
R1225ye(Z)	0.753	8.439	0.1059	4.796	0.7828	2.901	0.47	3.093	0.2443
R1234yf	0.753	8.439	0.1059	4.796	0.7828	2.828	0.465	3.136	0.2418

Table 4 shows the effect of low temperature cycle ecofriendly HFO refrigerants on the exergetic performances of cascaded ejector refrigeration system cascaded with vapour compression cycles R-1234ze(E)in the high temperature cycle and it was found that by using R1233zd(E), the minimum exergy destruction ratio along with the optimum (highest value of 24.99%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 144.93%. Table 5 shows the effect of low temperature cycle ecofriendly HFO refrigerants on the exergetic performances of cascaded ejector refrigeration system cascaded with vapour compression cycles R-1243zfin the high temperature cycle and it was found that by using R1233zd(E), the minimum exergy destruction ratio along with the optimum (highest value of 24.99 %) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 134.1%. Table-6 shows the effect of low temperature cycle ecofriendly HFO refrigerants on the exergetic performances of cascaded ejector refrigeration system cascaded with vapour compression cycles using R1224yd(E) in the high temperature cycle and it was found that by using R1233zd(E), the minimum exergy destruction ratio along with the optimum (highest value of 25.1%) second law exergy efficiency which is can be achieved and percentage improvement in exergy efficiency is to be found as 155.37%.

Table 4 :Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector VCR system using R1234ze(E)ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS(T_{boiler}=353(K), T_{eva} =263(K), T_{cond} =303(K), T_o=300(K), (L/D) =10, D_throat =0.0005 metre, D_m =0.0014 metre, D_p=0.0008metre, Diffuser angle =3^o Diffuser Length (L_d) =(112/1000) metre, Area Ratio =7.84, Q_eva =4.75 "kW", T_{eva_LTC} =223(K), Ambient temperature (To) =298K)

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrainment Ratio	Compression Ratio	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
HFO1336mzz(Z)	0.7296	8.783	0.1026	3.896	0.8684	2.907	0.4574	3.03	0.2482
R1233zd(E)	0.7296	8.783	0.1026	3.896	0.8684	2.976	0.4614	2.98	0.2513
R1225ye(Z)	0.7296	8.783	0.1026	3.896	0.8684	2.901	0.4571	3.021	0.2484
R1234yf	0.7296	8.783	0.1026	3.896	0.8684	2.828	0.4527	3.063	0.2461

Table 5 :Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector VCR system using R1243zf ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS(T_{boiler}=353(K), T_{eva} =263(K), T_{cond} =303(K), T_o=300(K), (L/D) =10, D_throat =0.0005 metre, D_m =0.0014 metre, D_p=0.0008metre, Diffuser angle =3^o Diffuser Length (L_d) =(112/1000) metre, Area Ratio =7.84, Q_eva =4.75 "kW", T_{eva_LTC} =223(K), Ambient temperature (To) =298K)

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrainment Ratio	Compression Ratio	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
HFO1336mzz(Z)	0.7586	8.370	0.1067	3.607	0.8792	2.907	0.4784	3.054	0.2467
R1233zd(E)	0.7586	8.370	0.1067	3.607	0.8792	2.976	0.4825	3.004	0.2498
R1225ye(Z)	0.7586	8.370	0.1067	3.607	0.8792	2.901	0.4780	3.045	0.2472
R1234yf	0.7586	8.370	0.1067	3.607	0.8792	2.828	0.4735	3.087	0.2447

Table 6 :Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector VCR system using R1224yd(Z) ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS($T_{\_boiler}$=353(K), $T_{\_eva}$ =263(K), $T_{\_cond}$ =303(K), T_o=300(K), (L/D) =10, D_throat =0.0005 metre, D_m =0.0014 metre, D_p=0.0008metre, Diffuser angle =3° Diffuser Length ($L_{\_d}$) =(112/1000) metre, Area Ratio =7.84, Q_eva =4.75 "kW", $T_{\_eva\_LTC}$ =223(K), Ambient temperature (To) =298K)

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrainment Ratio (shy)	Compression Ratio (mu_1)	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
HFO1336mzz(Z)	0.7025	9.118	0.09883	4.977	0.7991	2.907	0.4430	3.033	0.2480
R1233zd(E)	0.7025	9.118	0.09883	4.977	0.7991	2.976	0.4469	2.983	0.2511
R1225ye(Z)	0.7025	9.118	0.09883	4.977	0.7991	2.901	0.4427	3.024	0.2485
R1234yf	0.7025	9.118	0.09883	4.977	0.7991	2.828	0.4385	3.066	0.2459

5. Conclusions

Following conclusions were drawn

- The optimum exergy efficiency is to be found by using HFO-1336mzz(Z) and percentage improvement is 150.0% as compared by using R1225ye(Z)which has 134.85%improvement
- The 11.30% improvement can be achieved by using HFO-1336mzz(Z) in low temperature cycle as compared to R1225ye(Z) used in low temperature cycle.
- The optimum second law exergetic efficiency is to be found by using HFO-1336mzz(Z) and percentage improvement is 155.4% (using R1224yd(Z)as compared by using R-1234ze(Z) which has 133 % improvement
- The 16.77% improvement can be achieved by using HFO-1224yd(Z) in high temperature cycle as compared to R1234ze(Z) used in high temperature cycle.

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