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RESEARCH PAPER

Performance Evaluation of Ejector Refrigeration Systems (ERS) Cascaded with Vapour Compression Refrigeration Systems Using Low GWP Refrigerants

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ABSTRACT

Presently, the refrigeration and air conditioning is observing for energy efficient technologies which will decrease the electric power consumption from producing the damage to the environment. The ejector refrigeration system is originated to be energy efficient system which will be able to deliver the cooling by using the environment friendly refrigerants. In this paper, the effect of ecofriendly refrigerants in high temperature cycle between condenser temperature at 303K and evaporator temperature at 263K and low temperature cycle has evaporator temperature at 223K with constant temperature overlapping between high temperature evaporator and low temperature condenser on the thermodynamic Performance of Ejector Refrigeration Systems (ERS) cascaded with Vapour Compression Refrigeration Systems for ultra low a temperature application is investigated and comparison were made with other HFO refrigerants.
Key words: *Energy-Exergy analysis, Ejector refrigeration system, Thermodynamic performance*

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INTRODUCTION

With the fast development, the demand of energy is raising expontially taking place in the different parts of the world. The increase in global energy consumption across the world has led to use of fossil fuel at the very quicker rate. These fossil fuels are not depleting only at a quicker rate but also producing the global warming of the earth rapidly. Without causing the global warming, the market of refrigeration & heat pumps and air conditioning industries, is also facing the challenges of fulfilling the requirements of cooling and space heating. Still in the domestic and industrial sectors, a large share of the refrigerators and air conditioners installed for different applications are working on the vapour compression cycle. By the year 2100, it is predicted that as the economy of the developing countries improve, the worldwide power consumption for air conditioning systems working on vapour compression cycle will increased by 33%. This equipment's consumed the electrical power to provide the running the compressor. The use of CFC, HCFC and HFC is banned after the Kyoto and Montreal Protocols. Most of the refrigerants used in domestic and industrial areas are running on the alternate refrigerants which have high GWP.

Normally VCRS uses CFC, HFC and HCFC refrigerants and their leakages from the system causes the emissions in the environment, hence degrading its air quality. The emissions occurred in the system can be direct emissions or indirect emissions. The direct emissions results when there is a leakage of the refrigerants into atmosphere of earth. Around 27 to

30% of HC (hydrocarbons) and HFC (Hydro fluorocarbons) are released in to the atmosphere in the form of leakage while indirect emissions are the by products of the consumptions of electrical power which was derived from the fossil fuels. As of today, the refrigeration and air conditioning is looking for energy efficient technologies which will reduce the electrical power consumption apart from causing the damage to the environment. The ejector refrigeration system is one of such energy efficient technology which is able to compress the refrigerant in the system using the energy of the primary flow, However, the ejector refrigeration systems can provide the cooling by utilizing the environment friendly refrigerants (Mishra, 2020 a).

CHALLENGES OF VCRS USED IN REFRIGERATION AND AIR CONDITIONING

The throttling device in a refrigeration system usually assists two purposes. In the thermodynamics process, the liquid refrigerant is expanding from the condenser pressure to the evaporator pressure. The other one is the control function which may include the supply of the liquid to the evaporator at the rate at which it is evaporated. Therefore the irreversibility associated with throttling is major issue in vapour compression refrigeration cycle. There are several methods to reduce the throttling energy losses in the refrigeration cycles. In the conventional vapour compression refrigeration cycle, by using ejector as an expansion device which can replace, the throttling valve is an optimistic alternative to reduce the throttling losses in terms of expansion irreversibility in the refrigeration system due to its modest structure, comfort manufacturing with no moving parts and has low cost and low maintenance requirements. The ejector reduces the compressor work by raising the suction pressure to a level higher than that of which in turn improves COP of the system. It also enables to reduce size of the evaporator (Mishra, 2020 b).

Padilla, *et al*., (2010) explained thermodynamic analysis of domestic vapour compression refrigeration system with R12 and R413a using energy principle and concluded that the thermodynamic performances in terms of power consumption and the energy efficiency of R413A is improved than R12. Using regression analysis, Getu and Bansal (2008) had optimized the design operating parameters of cascade refrigeration system using R717in high temperature cycle and R744 in low temperature cycle and evaluated the performances using energetic analysis, with the help of first law analysis. The irreversibility destruction (or Exergy losses) in components of a system unable to determined. Therefore exergetic analysis is the advanced approach for thermodynamic performances is very essential for finding irreversibility in terms of exergy destruction occurred in the various components of simple and cascaded vapour compression refrigeration systems by Mishra, 2020 c. According to the European Parliament Directive 517/2014, the use of refrigerants with high global warming potential (GWP) has to be abridged. A universal limit in the GWP can be selected at 150, particularly for the domestic refrigeration systems and so the use of refrigerants with lower GWP has to be used in the new systems or to replace the present HFC and HCFC refrigerants. In current years, the fourth generation hydro-fluoro-olefins R1234yf and R1234ze are being considered as alternative to R134a. Many of studies have been supported by using HFO 1234yf and HFO-R1234ze. The European Union (EU) regulation is phasing out the current generation HFCs like R134a due to its high GWP and environment consequences. The European Union (EU) regulation is phasing out the current generation HFCs like R134a due to its high GWP and environment consequences. Mishra 2014 studies have been carried out using R1234yf and R1234ze(E) and found that The R1234ze(Z) gives better thermodynamic performances than R1234ze(E) and R1243zf. The thermodynamic performance of R1224yd (Z) and HFO-1336mzz(Z) is nearly similar and higher than R1234ze(E) but lower than R1224yd(Z). However R1234yf gives lowest thermodynamic performances. Mishra 2014 analyzed the hydro-fluoro-olefines (HFO) and hydro chloro-fluoro-olefines (HCFO) used in vapour compression refrigeration systems. The HFO

R1234yf and R1234ze (E) as well as the HCFO R1233zd(E) and R1224yd(Z) are especially promising low-GWP alternatives to the HFC R134a and R245fa. For instance, the German Environment Agency intends to prohibit the application of R1233zd(E), due to its ODP of 0.00024. However, R1233zd(E) has several favorable aspects, such as a very low GWP and no flammability and toxicity (safety classification of A1). This proves, that the very small ODP by R1233zd(E) and R1224yd lead to no significant increase of the external costs. Thus, a general prohibition of potentially promising refrigerants with a very small ODP appears not be justifiable based on the presented results.

The electrical powers are lower by using HCFO-1233zd(E) as compared to R134a As a conclusion, it can be stated, that both novel fluids R1233zd(E) and R1224yd(Z) are suitable for the drop-in replacement of R245fa in refrigeration systems (Mishra 2013). However, the results show, that the compatibility of R1233zd(E) and R1224yd(Z), with the is compared to replace R245fa and R134a, it is found that when R1233zd(E)is used, for finding the system performances, the highest power output is still obtained with the high-GWP fluid R245fa and R134a which is 7% to 9%. The exergy of fuel with R245fa is 0.40% higher compared to R1233zd(E) and 8% higher compared to R1224yd(Z). In terms of thermodynamic efficiency of the Organic Rankine Cycle (ORC) system, However, ecofriendly R1233zd(E) has around two percentage higher values equated to R245fa. Similarly the thermodynamic efficiency of HFC-245fa and R1224yd(Z) has identical and similar range of operating conditions. However R-1336mzz(E) (also referred to as HFO1336mzz(Z)) also provides thermodynamic property information for cis-1,1,1,4,4,4-Hexafluoro-2-butene, with molecular weight of 164.056 gm/mole, CAS# 692-49-9. The basics of selecting a good working refrigerants are based on system optimization to optimized the first and second law efficiencies for which these novel HFOs are being developed has characteristics of lower GWP with ultralow ODP of a good working fluids stability, compatibility, favourable toxicity and performance even at high temperatures also. The HFO-1336mzz(E) has 7.5^{o}C boiling point, critical temperature of 137.6^{0}C and critical pressure of 3.15 MPa. However HFO-1336mzz(Z) has a little higher boiling point of 33.4^{0}C, and also has 171.3^{0}C of critical temperature along with 2.90 MPa of lower critical pressure. The compressor efficiency, superheat, sub cooling and lift temperatures were fixed variables is this calculation, the condensing temperatures were adjusted so higher temperature effects could be evaluated for each working fluid. HFO1336mzz isomers (E and Z) and had the excellent first law efficiency (COPs) amongst than the HFC Refrigerants (such as R134a, R410a, R404a, R407c, R507a, R125a) but lower than R245fa due to and power required to run compressors is 8.63% higher than R245fa. Mishra 2020 (e), performed exergy analysis on a vapour compression refrigeration systems using liquid vapour heat exchanger and several HFO refrigerants (i.e. R1234yf, R1234ze(Z) R1234ze(E), R1243zf, R1224yd(z), R1225ye(z) and HFO-1336mzz(Z)) for replacing R134a refrigerants. The HFO refrigerants were good alternatives to R134a regarding their environment friendly properties. The ecofriendly refrigerants such as R134a, R1234yf, and R1234ze(E) are the pure substances.

The HFO (hydro-fluoro-olefin) are going to be our future refrigerants with low ozone depletion potential (ODP) and low global warming potential (GWP). The basic properties of new future HFO refrigerants expected as R134a and R32 alternatives which are presently used in refrigerators. R1243zf is probably to be a good alternative with its flammability, which is A2 category for replacing R134a. Attila Gencer, *et al*. (2018) have theoretically evaluated the thermodynamic behaviour in terms of energy parameters (i.e., cooling capacity and COP) for three different vapour compression refrigeration systems (i.e. basic cycle, basic cycle with liquid-to-suction heat exchanger and two-stage cascade cycle) and compared exergetic efficiency using low GWP alternative refrigerants (i.e. R1234yf, R1234ze(E), R513A, R445A and R450A) for replacing R134a. The comparison of the energy parameters for two different evaporation temperatures (-30°C and 0°C) and two condensing temperatures (40°C and 55°C) was carried out and numerical results shows that R450A which almost has the same COP values as R134a comes into prominence with 58% lower GWP value compared to R134a and suggested that R445A gives highest exergetic efficiency with liquid shell heat exchanger. Also concluded that the studied refrigeration cycles, system for providing a better effect in terms of COP for the considered refrigerants and temperature cases as well as assumed system parameters and found that system with liquid shell heat exchanger gives better effect in terms of COP for the considered refrigerants and temperature cases as well as assumed system parameters. Sanchez, *et al*. (2017) compared five low GWP refrigerants R152a, R1234yf, R1234ze, R290 and R600a for the replacement of R134a using hermetic compressor in the experimental test rig and found that the R1234yf can be considered suitable drop-in alternative to R134a by considering the energy consumption and the cooling refrigerating capacity of facility. Mota-Babiloni, *et al*. (2014, 2015 a&b) evaluated energy performances of two low-GWP refrigerants such as R1234yf and R1234ze(E), as drop-in replacements for R134a and conducted various tests in vapour compression system by combining different values of evaporation and condensation temperature and without/ with the adoption of an internal heat exchanger. The above investigators have not evaluated the performance of cascaded ERS with VCRS using ultralow GWP refrigerants. The effect of HFO refrigerants in high temperature cycle and low temperature cycleof cascaded ERS system is investigated.

RESULTS AND DISCUSSION

Following Numerical values have been chosen for numerical computation shown in table1.

Input data in High Temperature Cycle	Ejector geometric input data	Input data in Low temperature Temperature Cycle
Boiler temperature ejector refrigeration (T_{boiler}) =353(K) Evaporator temperature of ejector refrigeration (T_eva) = 263(K) Condenser temperature of ejector refrigeration (T_cond) =303(K) Ambient temperature (To) = 300(K) Refrigerant used in ejector refrigeration system = R1234ze(Z), R1234ze(E), R1243zf and R1224yd(Z)	{Length / Diameter} ratio of constant area mixing chamber(L/D) of ejector = 10 Diameter of primary nozzle throat (D_throat) metre = (0.5/1000) Diameter of mixing chamber (D_m) metre = (1.4/1000) Exit diameter of primary nozzle (D_p) metre = (0.8/1000) Diffuser angle(theta) = 3° Diffuser Length (L_d) metre = (112/1000) Area Ratio = 7.84	Cooling Load of ejector refrigeration system (Qeva) = 4.75 "kW" Evaporator temperature of low temperature cycle (T_eva) = 223(K) Condenser temperature of low temperature refrigeration cycle (T_cond_LTC) = T_Eva+Approach Ambient temperature (To) = 300(K) Refrigerant used in low temperature refrigeration system = R1225ye(Z), R1233zd(E) and HFO-1336mzz(Z) Compressor efficiency = 80%

Table 1: Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector vapour compression refrigeration system using HFO-1336mzz(Z) in low temperature cycle and following ecofriendly refrigerants in high temperature cycle

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: Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle and following ecofriendly refrigerants in high temperature cycle

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 vapour compression refrigeration system using R1234ze(Z) ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrain-ment Ratio (shy)	Comp-ression Ratio (mu_1)	COP_ VCRS	Cascade COP	Cascade EDR	Cascade Exergetic Efficiency
HFO1336mzz(Z)	0.7531	8.439	0.1059	4.796	0.7828	2.907	0.4898	3.102	0.2438
R1233zd(E)	0.7531	8.439	0.1059	4.796	0.7828	2.976	0.4739	3.052	0.2468
R1225ye(Z)	0.7531	8.439	0.1059	4.796	0.7828	2.901	0.4694	3.093	0.2443
R1234yf	0.7531	8.439	0.1059	4.796	0.7828	2.828	0.4649	3.136	0.2418

Table 4: Variation of evaporator temperature with thermodynamic performances of VCRS cascaded ejector vapour compression refrigeration system using R1234ze(E) ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS

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 vapour compression refrigeration system using R1243zf ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrain-ment Ratio	Comp-ression 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 vapour compression refrigeration system using R1224yd(Z) ecofriendly refrigerant in ejector refrigeration system (ERS) and following ecofriendly refrigerants in VCRS

Refrigerants in LTC	COP_ ERS	EDR_ ERS	Exergetic Efficiency	Entrain-ment Ratio (shy)	Comp-ression 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

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 150.098%.

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 24.98%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 134.844%. From table-1 and table -2, The highest second law exergetic efficiency is to be found by using HFO-1336mzz(Z) and percentage improvement is 150.098% 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-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 24.98%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 144.932%

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-1243zf 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 134.114%.

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 25.11%) second law exergetic efficiency which is can be achieved and percentage improvement in exergetic efficiency is to be found as 155.365%

CONCLUSION

Following conclusions were drawn-

1. The optimum 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)which has 134.84% improvement.
2. The 11.31% improvement can be achieved by using HFO-1336mzz(Z) in low temperature cycle as compared to R1225ye(Z) used in low temperature cycle.
3. The optimum second law exergetic efficiency is to be found by using HFO-1336mzz(Z) and percentage improvement is 155.37% (using R1224yd(Z)as compared by using R-1234ze(Z) which has 133.05% improvement.
4. 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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