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ORIGNAL ARTICLE

Thermal performance evaluation of modified vapour compression refrigeration systems using multiple compressors, evaporators & expansion valves using HFO refrigerants

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Abstract

This paper mainly deals with thermodynamic performance evaluation of ultra-low GWP eight ecofriendly HFO & HCFO refrigerants in the multi vapour compression refrigeration system using multi evaporators, multi compressors, multi expansion valves, inter cooler, flash chambers based on energetic and exergetic principles for finding first law efficiency and second law efficiency, exergetic efficiency and exergy destruction ratio of modified vapour compression refrigeration systems. system performance parameters have been evaluated by using entropy generation(irreversibility) concept. The numerical computation was carried out for finding rational exergy destruction ratio based on system exergy input in terms of total work done by compressors (exergy of fuel) as well as exergy destruction ratio based on exergy of product out and first law efficiency in terms of COP. The second law efficiency in terms of exergetic efficiency is also computed at different input variations. It was found Flash chamber responsible for highest exergy destruction for all refrigerants taken under consideration. R1234ze(Z) shows best first law efficiency and R1234yf shows lowest first & second law performance among selected eight HFO ecofriendly refrigerants. It was found that the first and second law performances of using R1234ze(Z) is better than R1234yf for higher temperature applications.

1. Introduction

An eminent philosopher has defined Science as "Tapasaya" and Technology as "Bhog" whereas science is pure selfless and open to all search for truth whereas technology is the exploitation of scientific knowledge for selfish purposes and profit motive and hence it tends to be secretive in this competitive world of today with a throat cutting environment. Sustainable Development is a process in which development can be sustained for generations. It also focuses attention on inter-generational fairness in the exploitation of development opportunities while social development is a function of technological advancement, and also the technological advancement, in turn is a function of scientific know how for a streamlined development of the society. Technology is one of the crucial determinants of sustainable development. Technological import through collaborations has been one of the most important sources of technological inputs for Indian conditions. The use of technologies originating in rich countries often ten to create many social, ecological and

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resource problems in poor countries. The exploitation of the vast natural resources through progressive development of science, engineering and technology that has brought about the vast changes in the civilization and society from the stone age to the present high technology era. In facts, the mad race for industrialization and economic development has resulted in over exploitation of natural resources, leading to a situation where the two worlds of mankind- the biosphere, lithosphere and hydrosphere of his inheritance and the techno sphere of his creation, are out of balance with each other, indeed on a collision path.

To facilitate optimal utilization of finite natural resources for ensuring a sustainable benefit steam for better quality of life on the one hand and to simultaneously keep in mind the conservation of natural resources on the other hand, it is essential that the technology conservation process must be made as efficient as possible. Therefore, sustainable economic development depends on the careful choice of technologies and judicious management of resources for productive activities to satisfy the changing human needs without degrading the environment or depleting the natural resources base [1].

2. Ecofriendly HFO Refrigerants used in modified vapour compression refrigeration systems

In the vapour compression refrigeration systems/ heat Pumps well defined by several investigators. The efforts under the Montreal protocol to protest the ozone layer, the alternative refrigerants have been proposed as a substitute for ozone depleting substances. Although HFCs (Hydro-fluorocarbons) PFCs (Perflurocarbons) have zero ODP potential but they are producer of greenhouse gases and are subjected to limitation [2] and reduction commitments under UNFCC (United Nations Framework Convention on Climate change). With the entry into force of Kyoto protocol on 16th February 2005 developed countries have already planning and implementing rational measures intended to contribute towards meeting greenhouse gas reduction targets during the first commitment period of Kyoto protocol (2008-2012). The countries have also started together with developing countries to size up projects that qualify under Kyoto clean development mechanism. As what lies beyond 2012 and all Governments should work together over next few years to decide on future intergovernmental action on the climate change [2]

After 90's CFC and HCFC refrigerants have been restricted due to presence of chlorine content and their high ODP and GWP. Thus, HFC refrigerants are used nowadays, showing much lower global warming potential value, but still high with respect to non-fluorine refrigerants. Many researchers have been done for replacing of "old" refrigerants with "new" refrigerants. In this light, it is vital that there should be continuous work on the replacement options for ozone depleting substances in way that serve the aim of the Montreal protocol and UNFCC alike. In the developing countries the conversion of CFCs to alternate is still a major issue. In this paper the first law and second law analysis of various ecofriendly refrigerants have been carried out which will help in deciding about the path to be followed to satisfy Montreal and Kyoto protocol. On the basis of theoretical analysis and It was observed that R-134a refrigerant is the best alternative [3] Now a day's most of the energy utilize in cooling and air conditioning in industrial as well a domestic application. In addition, with energy consumption, using of refrigerants in cooling and air conditioning having high GWP and ODP are responsible for global warming and ozone depletion [4].

The primary requirements of ideal refrigerants are having good physical and chemical properties, due to good physical and chemical properties such as non-corrosiveness, non-toxicity, non- flammability, low boiling point, Chlorofluorocarbons (CFCs) have been used over the last many decades. But hydro-chloro-fluorocarbons (HCFCs) and Chlorofluorocarbons (CFCs) having large amount of chlorine content as well as high GWP and ODP, so after 90s refrigerants under these categories are almost prohibited [5-6]. Most of the studies have been carried out for the performance evaluation of vapour compression refrigeration system using energetic analysis [7-17]. But with the help of first law analysis irreversibility destruction or losses in components of system unable to determined, so exergetic or second law analysis is the advanced approach for thermodynamic analysis which give an additional practical view of the processes. In addition to this second law analysis also provides new thought for development in the existing system. These scientists did not gone through second law analysis in terms of system defect defined as irreversibility calculations in various components of vapour compression refrigeration Therefore objective of the present investigations to find out irreversibility's occurred in the components of vapour compression refrigeration systems because second law analysis is very useful for finding the irreversibility in components as well as in whole system it is a powerful tool for designing and analyzing of air conditioning and refrigeration systems. The utility of energy and exergy analysis in Vapour Compression Refrigeration Systems is well documented by several investigators [18]. The first law analysis using for evaluation of coefficient of performance having values greater than unity for certain processes. The first law of thermodynamics is concerned only with the conservation of energy, and it gives no information on how, where, and how much the system performance is degraded, exergy analysis is a powerful tool in the design, optimization, and performance evaluation of energy systems. Because exergy analysis (second law analysis) helps in identifying the thermal losses (exergy destruction in each components) and energy transfer in the thermodynamic processes [19].

Yumrutas et al. [20] carried out exergy analysis based investigation of effect of condensing and evaporating temperature on vapour compression refrigeration cycle in terms of pressure losses, COP, second law efficiency and exergy losses. Variation in temperature of condenser as well as have negligible effect on exergy losses of compressor and expansion valve, also first law efficiency and exergy efficiency increase but total exergy losses of system decrease with increase in evaporator and condenser temperature.

Padilla et al. [21] exergy analysis of domestic vapour compression refrigeration system with R12 and R413A was done. They concluded that performance in terms of power consumption, irreversibility and exergy efficiency of R413A is better than R12, so R12 can be replaced with R413A in domestic vapour compression refrigeration system.

Halimic et al. [22] compared performance of R401A, R290 and R134A with R12 by using in vapour compression refrigeration system, which is originally designed for R12.Due to similar performance of R134a in comparison with R12, R134A can be replaced in the same system without any medication in the system components. But in reference to greenhouse impact R290 presented best results. `

Bolaji et al. [23] had done experimentally comparative analysis of R32, R152a and R134a refrigerants in vapour compression refrigerator. They reached to the conclusions that R32 shows lowest performance whereas R134a and R152a showing nearly same performance but best performance was obtained of system using R152a.

Getu and Bansal [24] had optimized the design and operating parameters of like condensing temperature, sub-cooling temperature, evaporating temperature, superheating temperature and temperature difference in cascade heat exchanger R744-R717 cascade refrigeration system. A regression analysis was also done to obtain optimum thermodynamic parameters of same system.

For low GWP and zero ODP refrigerants are required for better energy characteristics first law efficiency (COP) and second law thermal performances (exergy destruction ratio and exergetic efficiency) should be preferred [25-30].

R.S. Mishra [31-40] represents that all new alternative gases are better regarding their lower GWP values. Although they have some differences in terms of energy parameters, it can be stated that R-1234ze and R1234yf, R-152a and R245fa refrigerants will be good alternatives to R134a, R404A, R410A and R22, respectively and suggested that above refrigerants can replace R-134a in vapour compression refrigeration cycles.

Various hydro-fluoroolefins (HFOs) and hydrochloro-fluoroolefins (HCFOs) have recently been developed, which exhibit ultra-low GWPs, are non-flammable and are showing potential for use at high, medium, low and ultra-low temperatures (i.e. below -150°C). The thermodynamic properties of these refrigerants allow subcritical VCRS at condensation temperatures in the range of about 40 to 60°C [41-42].

Mishra [43-45] investigated the environmentally friendly HFOs R1336mzz(Z) and R1234ze(Z) and the HCFOs R1233zd(E) and, R1243zf, R 1225ye(Z) R1234yf, R1234ze(E) in the vapour compression refrigeration systems with a variable-speed reciprocating compressor and compares the coefficient of performance (COP) and the exergetic efficiency with the HFC refrigerants R152a, R-32, R134a and R245fa at different condensation and evaporator temperatures up to -30^{o}C and. R1224yd(Z) up to -10^{o}C respectively with internal heat exchanger is used for adequate superheating purpose. Based on thermal analysis numerical computation was carried out for single stage and multi stages VCRS it is found that, a single-stage VCRS with internal heat exchanger using R1234ze(Z) and the HCFOs R1233zd(E) and R1224yd(Z) has been used to compute thermodynamic first and second law performances of various refrigerants for provides 70 kW cooling capacity for temperature of -30^{o}C in single stages VCRS and from -50^{o}C to -155°C in multi stages cascaded VCRS.

Similarly, the system design, theoretical simulations and first experimental test results with a single-stage high temperature heat pump (HTHP) with internal heat exchanger using R1234ze(E) and R1225ye(Z), R-1336mzz(Z) are suitable for low temperature applications [46]

Due to increasing awareness of global warming, the types of refrigerants used in heat pumps are changing globally. Regulations for HFC refrigerants are being introduced due to their high global warming potential (GWP). This can create a shift in demand for different refrigerants since HFCs are still commonly used in many countries. As a result, the refrigerant charge will play a significant role when determining the most feasible refrigerant. M. Direk, AlperKelesoglu, A. Akin [46] theoretically investigated, the effects of internal heat exchanger effectiveness on the performance parameters of the refrigeration cycle using R1234yf and developed mathematical model based on the energy balance of the cycle. The thermal analysis was performed between -20°C and 0°C evaporation and 40°C and 50°C condensation temperatures based on the effectiveness value of IHX. The cooling capacity, coefficient of performance (COP), sub-cooling, superheat and compressor discharge temperature of the refrigeration cycle was examined. Finally, the performance results of the cycle with R1234yf were compared in the same baseline cycle with that utilized R134a at same 50% effectiveness for comparing results. Nielsen and S. Thorsén [47] presented a numerical study of the performance of natural, HFC, and HFO refrigerants for a one-stage cycle and focused on the refrigerant charge influence and found that natural refrigerant ammonia (R717) is the most optimal refrigerant, exhibiting a 51% to 87% smaller charge and 12% to 27% lower cost of heat compared to other refrigerants.

3. Results and Discussion

Following modified vapour compression refrigeration systems have been used for numerical computations for predicting exergetic performances [48].

System-1

Modified vapour compression refrigeration system using multiple evaporators, single compressor with single expansion valves (Q_{Eva_1}=35 "kW, Q_{Eva_2}=70 "kW, Q_{Eva_3}=35 "kW, $T\_{EVA\_}$=268K,, Eff_{Comp}=0.75, T_Cond=313K, with subcooling of liquid at condenser out let at 303K)

System-2

Modifiedvapour compression refrigeration system using multiple evaporators, single compressor with individual expansion valves (Q_{Eva_1}=35 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW,T_{EVA_2}=273K, Q_{Eva_3}=35 "kW,T_{EVA_3}=283K, Eff_{Comp}=0.75, T_Cond=313K, with subcooling of liquid at condenser out let at 303K,)

System-3

Modified vapour compression refrigeration system using multiple evaporators, single compressor with multiple expansion valves (Q_{Eva_1}=105 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW,T_{EVA_1}=278K, Q_{Eva_3}=35 "kW,T_{EVA_1}=283K,Eff_{Comp}=0.75, T_{Cond}=313K, with sub-cooling of liquid at condenser out let at 303K)

System-4

Modified vapour compression refrigeration system using multiple evaporators, individual compressors with individual expansion valves (Q_{Eva_1}=35 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW,T_{EVA_2}=278K, Q_{Eva_3}=105 "kW,T_{EVA_3}=283K, Eff_{Comp}=0.75, T_Cond=313K, Sub-cooling=303K)

System-5

Modified vapour compression refrigeration system using multiple evaporators, individual compressors with multiple expansion valves (Q_{Eva_1}=70 "kW, T_{EVA_1}=268K, Q_{Eva_2}=105 "kW T_{EVA_2}=273K, Q_{Eva_3}=35 "kW, T_{EVA_3}=278K, Eff_{Comp}=0.75, T_{Cond}=313K,,Eff_{Comp}=0.75, with sub-cooling of liquid at condenser out let at 303K).

System-6

Modified vapour compression refrigeration system using multiple evaporators, compound compression with individual expansion valves with flash intercooler (Q_{Eva_1}=105 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW, T_{EVA_2}=278K, Q_{Eva_3}=35 "kW, T_{EVA_3}=283K, Eff_{Comp}=0.75, T_{Cond}=313K, with subcooling of liquid at condenser out let at 303K, Efficiency $\_{Comp}$=0.75)

3.1 *Effect of HFO refrigerants using multiple compressors in modified systems with different evaporator loads*

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, the performance parameters are presented in Table-1 respectively. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system-1 using R1234ze(Z) is 4.4% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. Similarly, the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The second law efficiency of modified system-1 is also behaving in the same manner because it is a ratio of actual first law efficiency (COP_{Actual} / COP_{Carnot}). while exergetic efficiency of modified system, which is a ratio of exergy of product (kw) to the exergy of fuel (kW) in terms of total compressor work is also behaving in the similar manner. When system end state becomes dead state (i.e. at temperature of 298K), the exergetic efficiency becomes second law efficiency. It is found that second law efficiency and exergetic efficiency of modified system-1 is highest by using R-1234ze(Z). and exergetic efficiency is much lower than second law efficiency. This is due to that second law efficiency is computed by COP of Carnot at condenser and evaporator difference instead of difference between dead state temperature minus evaporator temperature. Similarly, by using R1224yd(Z), R1233zd(E) and R-1336mzz(Z), R-1243zf, R1225ye(Z) and R1234ze(E), the first law efficiency, second law efficiency and exergetic efficiency is much higher than using R1234yf. Similarly, by using R-1234yf, the compressor work (exergy of fuel in kW) is highest. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future.

Table-1 Multiple evaporators at the same Temperatures with single isentropic compression, individual expansion valves using R12 (Q_{Eva_1}=35 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW, T_{EVA_2}=273K, Q_{Eva_3}=35 "kW,T_{EVA_3}=283K, Eff_{Comp}=0.75, T_{Cond}=313K, Eff_{Comp}=0.75%)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.051	3.885	3.999	4.029	3.846	3.973	3.864	3.75
Exergy destruction Ratio (EDR)	1.666	1.762	1.697	1.68	1.788	1.715	1.776	1.849
Exegetic efficiency	0.3710	0.3557	0.3662	0.3690	0.3522	0.3638	0.3536	0.3434
Second Law efficiency	0.6803	0.6523	0.6714	0.6766	0.6458	0.6671	0.6488	0.6297
Total Compressor Work "kW"	51.54	54.06	52.52	52.12	54.6	52.86	54.35	55.99
Exergy of Fuel"kW"	51.54	54.06	52.52	52.12	54.6	52.86	54.35	55.99
Exergy of Product "kW"	23.51	23.51	23.51	23.51	23.51	23.51	23.51	23.51

The performance parameters using HFO refrigerants, with compressor efficiency is 75% in the actual conditions are presented in Table-2 respectively. It is found that the first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-1234yf, the COP of modified system-2 using R1234ze(Z) is highest. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. Similarly, the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The second law efficiency of modified system-2 is also a ratio of actual first law efficiency ($COP_{\_Actual}$ / $COP_{\_Carnot}$). and exergetic efficiency of modified system, is a ratio of exergy of product (kw) to the exergy of fuel (kW) in terms of total compressor work are behaving in the similar manner. When system end state becomes dead state (i.e. at temperature of 298K), the exergetic efficiency becomes second law efficiency. It is found that second law efficiency and exergetic efficiency of modified system-1 is highest by using R-1234ze(Z). and exergetic efficiency is much lower than second law efficiency. This is due to that second law efficiency is computed by COP of Carnot at condenser and evaporator difference instead of difference between dead state temperature minus evaporator temperature. Similarly, by using R1224yd(Z), R1233zd(E) and R-1336mzz(Z), R-1243zf, R1225ye(Z) and R1234ze(E), the first law efficiency, second law efficiency and exergetic efficiency is much higher than using R1234yf. Similarly, by using R-1234yf, the compressor work (exergy of fuel in kW) is highest. Therefore it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future.

Table-2 Multiple evaporators at the Different Temperatures with single compressor, individual expansion valves ($Q_{\_Eva\_1}$=35 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 "kW, $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 "kW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, T_Cond=313K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf	R-134a	R1233 zd(E)
First law efficiency (COP)	3.266	3.037	3.199	2.997	3.162	3.024	2.876	3.014	3.239
Exergy destruction Ratio (EDR)	2.969	3.348	3.194	3.382	3.361	3.28	3.626	3.161	3.026
Exergetic efficiency	0.2541	0.2462	0.2438	0.2457	0.2352	0.2506	0.2390	0.2566	0.2627
Second Law efficiency	0.4994	0.4751	0.4835	0.4719	0.4717	0.479	0.4563	0.4867	0.5069
Total Compressor Work "kW"	53.59	57.62	54.7	58.4	55.35	57.88	60.85	57.55	54.22
Temperature at inlet of compressor(K)	276.5	275.1	276.9	275.4	277.4	275.2	275.1	274.8	275.6
Exergy of Fuel"kW"	53.59	57.62	54.7	58.4	55.35	57.88	60.85	57.55	54.22
Exergy of Product "kW"	13.62	14.19	13.33	14.35	13.02	14.5	14.54	14.77	13.30

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, the performance parameters are presented in Table-3 respectively. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-1234yf, the COP of modified system-1 using R1234ze(Z) is highest. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. Similarly, the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The second law efficiency of modified system-3 is also behaving in the same manner because it is a ratio of actual first law efficiency ($COP_{\_Actual}$ / $COP_{\_Carnot}$). while exergetic efficiency of modified system, which is a ratio of exergy of product (kw) to the exergy of fuel (kW) in terms of total compressor work is also behaving in the similar manner. When system end state becomes dead state (i.e. at temperature of 298K), the exergetic efficiency becomes second law efficiency. It is found that second law efficiency and exergetic efficiency of modified system-3 is highest by using R-1234ze(Z). and exergetic efficiency is much lower than second law efficiency. This is due to that second law efficiency is computed by COP of Carnot at condenser and evaporator difference instead of difference between dead state temperature minus evaporator temperature. Similarly, by using R1224yd(Z), R1233zd(E) and R-1336mzz(Z), R-1243zf, R1225ye(Z) and R1234ze(E), the first law efficiency, second law efficiency and exergetic efficiency is much higher than using R1234yf. Similarly, by using R-1234yf, the compressor work (exergy of fuel in kW) is highest. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future. The thermodynamic performances of modified systems (system-1,2,3) have been compared and it was found that system-1& system-3 gives higher first law performance (COP) as compared to system-2, while system-1 & system-3 have nearly similar performances with slightly difference. The performance parameters using HFO refrigerants, with compressor efficiency is 75% in the actual conditions are presented in Table-4 respectively. It is found that the first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-1234yf, the COP of modified system-4 using R1234ze(Z) is highest, Similarly, First law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. Similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a.

Table-3 Multiple evaporators at the Different Temperatures with compound compression, individual expansion valves and flash inter cooler (Q_{Eva_1}=105 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW, T_{EVA_1}=278K, Q_{Eva_3}=35 "kW,T_{EVA_1}=283K,Eff_{Comp}=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.054	3.904	4.015	4.042	3.864	3.994	3.876	3.775
Exergy destruction Ratio (EDR)	2.085	2.133	2.174	2.165	2.152	2.257	2.112	2.20
Exegetic efficiency	0.2986	0.2899	0.2878	0.2891	0.2879	0.2805	0.2918	0.2825
Second Law efficiency	0.5993	0.5818	0.5872	0.5903	0.5770	0.5778	0.5820	0.5649
Total Compressor Work "kW"	51.8	53.8	52.3	51.96	54.35	52.58	54.18	55.63
Exergy of Fuel"kW"	51.8	53.8	52.3	51.96	54.35	52.58	54.18	55.63
Exergy of Product "kW"	15.36	15.59	15.05	15.02	15.65	14.75	15.81	15.71

The second law efficiency of modified system-4 is also a ratio of actual first law efficiency (COP_{Actual} / COP_{Carnot}) and exergetic efficiency of modified system, is a ratio of exergy of product (kw) to the exergy of fuel (kW) in terms of total compressor work are behaving in the similar manner. When system end state becomes dead state (i.e. at temperature of 298K), the exergetic efficiency becomes second law efficiency. It is found that second law efficiency and exergetic efficiency of modified system-1 is highest by using R-1234ze(Z). and exergetic efficiency is much lower than second law efficiency. This is due to that second law efficiency is computed by COP of Carnot at condenser and evaporator difference instead of difference between dead state temperature minus evaporator temperature. Similarly, by using R1224yd(Z), R1233zd(E) and R-1336mzz(Z), R-1243zf, R1225ye(Z) and R1234ze(E), the first law efficiency, second law efficiency and exergetic efficiency is much higher than using R1234yf. Similarly, by using R-1234yf, the compressor work (exergy of fuel in kW) is highest. Therefore it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future

Table-4 Multiple evaporators at the Different Temperatures with single compressor, individual expansion valves (Q_{Eva_1}=35 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW, T_{EVA_2}=278K, Q_{Eva_3}=105 "kW, T_{EVA_3}=283K, Eff_{Comp}=0.75, T_Cond=313K, Subcooling=313K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	5.531	5.363	5.484	5.515	5.302	5.468	5.315	5.193
Exergy destruction Ratio (EDR)	2.319	2.40	2.342	2.328	2.429	2.352	2.422	2.486
Exergetic efficiency	0.2969	0.2874	0.2944	0.2961	0.2847	0.2936	0.2853	0.2788
Total Compressor Work "kW	37.97	39.23	38.29	38.08	39.61	38.41	39.51	40.44
Second Law efficiency	0.7361	0.7124	0.7298	0.7339	0.7056	0.7277	0.7073	0.7015
Exergy of Fuel"kW"	37.97	39.23	38.29	38.08	39.61	38.41	39.51	40.44
Exergy of Product "kW"	11.27	11.27	11.27	11.27	11.27	11.27	11.27	11.27
Mass flow rate in condenser	1.127	1.437	1.447	1.226	1.689	1.418	1.307	1.668
Mass flow rate in First Compressor(kg/s)	0.1986	0.2575	0.2583	0.2178	0.302	0.256	0.2323	0.3009
Mass flow rate in second Compressor (kg/s)	0.3755	0.4782	0.482	0.4084	0.5624	0.4772	0.4353	0.5552
Mass flow rate in thirdCompressor(kg/s)	0.5532	0.7010	0.7071	0.6001	0.8250	0.6901	0.6398	0.8123

3.2 Effect of HFO refrigerants using multiple compressors in modified systems with different evaporator loads

The performance parameters using HFO refrigerants, with compressor efficiency is 75% in the actual conditions are presented in Table-5 respectively. It is found that the first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-1234yf, the COP of modified system-5 using R1234ze(Z) is highest, Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. Similarly, the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The second law efficiency of modified system-5 is also a ratio of actual first law efficiency (COP_{Actual} / COP_{Carnot}). and exergetic efficiency of modified system, is a ratio of exergy of product (kw) to the exergy of fuel (kW) in terms of total compressor work are behaving in the similar manner. When system end state becomes dead state, the exergetic efficiency becomes second law efficiency. It is found that second law efficiency and exergetic efficiency of modified system-5 is highest by using R-1234ze(Z). and exergetic efficiency is much lower than second law efficiency. This is due to that second law efficiency is computed by COP_{Carnot} at condenser and evaporator difference instead of difference between dead state temperature minus evaporator temperature. Similarly, by using R1224yd(Z), R1233zd(E) and R-1336mzz(Z), R-1243zf, R1225ye(Z) and R1234ze(E), the first law efficiency, second law efficiency and exergetic efficiency is much higher than using R1234yf. Similarly, by using R-1234yf, the compressor work (exergy of fuel in kW) is highest.

Table-5 Multiple evaporators at the Different Temperatures with compound compression, individual expansion valves and flash inter cooler ($Q_{\_Eva\_1}$=70 “kW, $T_{\_EVA\_1}$=268K, ,$Q_{\_Eva\_2}$=105 “kW $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 “kW,$T_{\_EVA\_3}$=278K, $Eff\_{}_{Comp}$=0.75, $T_{\_Cond}$=313K,,$Eff\_{}_{Comp}$=0.75, Subcooling=303K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.724	4.601	4.693	4.715	4.556	4.685	4.563	4.475
Exergy destruction Ratio (EDR)	1.903	1.997	1.934	1.917	2.024	1.949	2.014	2.083
Exegetic efficiency	0.3559	0.3466	0.3535	0.3552	0.3432	0.3529	0.3438	0.3371
Second Law efficiency	0.5288	0.515	0.5254	0.5278	0.510	0.5244	0.5108	0.5010
Total Compressor Work “kW”	44.45	45.64	44.74	44.54	46.09	44.83	46.02	46.92
Exergy of Fuel“kW”	44.45	45.64	44.74	44.54	46.09	44.83	46.02	46.92
Exergy of Product “kW”	15.82	15.82	15.82	15.82	15.82	15.82	15.82	15.82
Mass flow rate insecond Compressor(m_2)	0.4989	0.6062	0.6306	0.5389	0.7114	0.6127	0.5543	0.6875
Mass flow rate in Firstevaporator(m_3)	0.1878	0.2391	0.241	0.2042	0.2812	0.236	0.2177	0.2776
Mass flow rate in First Compressor(kg/s)	0.3225	0.3872	0.4064	0.3476	0.4547	0.3942	0.3546	0.4372
Mass flow rate in second Compressor(kg/s)	0.4898	0.5915	0.6175	0.5282	0.6945	0.599	0.5416	0.6693
Mass flow rate in thirdCompressor(kg/s)	0.3259	0.4738	0.4413	0.3644	0.5582	0.4461	0.4234	0.5811

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, the performance parameters are presented in Table-6 respectively. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-1234yf, the COP of modified system-1 using R1234ze(Z) is highest, Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. Similarly, the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The second law efficiency of modified system-6 is also future behaving in the same manner because it is a ratio of actual first law efficiency ($COP\_{}_{Actual}$ / $COP\_{}_{Carnot}$). while exergetic efficiency of modified system, which is a ratio of exergy of product (kw) to the exergy of fuel (kW) in terms of total compressor work is also behaving in the similar manner. When system end state becomes dead state (i.e. at temperature of 298K), the exergetic efficiency becomes second law efficiency. It is found that second law efficiency and exergetic efficiency of modified system-6 is highest by using R-1234ze(Z). and exergetic efficiency is much lower than second law efficiency.

Table-6. Multiple evaporators at the Different Temperatures with compound compression, individual expansion valves and flash inter cooler ($Q_{\_Eva\_1}$=105 “kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 “kW, $T_{\_EVA\_2}$=278K, $Q_{\_Eva\_3}$=35 “kW,$T_{\_EVA\_3}$=283K, $Eff\_{}_{Comp}$=0.75, $T_{\_Cond}$=313K,$Eff\_{}_{Comp}$=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.616	4.529	4.598	4.613	4.485	4.597	4.486	4.421
Exergy destruction Ratio (EDR)	1.830	1.971	1.854	1.839	1.944	1.863	1.938	2.0
Exegetic efficiency	0.3666	0.3597	0.3652	0.3664	0.3562	0.3651	0.3563	0.3512
Second Law efficiency	0.6143	0.6027	0.6119	0.6139	0.5968	0.6118	0.5970	0.5884
Total Compressor Work “kW”	45.49	46.37	45.67	45.53	46.82	45.68	46.81	47.5
Exergy of Fuel“kW”	45.49	46.37	45.67	45.53	46.82	45.68	46.81	47.5
Compressor Work “kW	8.131	8.145	8.14	8.131	8.224	8.15	8.225	8.268
Compressor Work “kW	4.476	4.504	4.484	4.477	4.548	4.486	4.549	4.582
Compressor Work “kW	32.89	33.72	33.05	32.92	34.05	33.06	34.03	34.65
Exergy of Fuel“kW	45.49	46.37	45.67	45.53	46.82	45.68	46.81	47.5
Exergy of Product “kW”	16.68	16.68	16.68	16.68	16.68	16.68	16.68	16.68
Mass flow rate in first Compressor(m_{c1})	0.4915	0.5923	0.6213	0.5309	0.6949	0.6044	0.5411	0.6695
Mass flow rate in second evaporator (m_2)	0.3308	0.4019	0.4172	0.3567	0.472	0.4045	0.3681	0.4560
Mass flow rate in second evaporator ($m_2^{'}$)	0.01473	0.01127	0.01247	0.01239	0.01536	0.006735	0.0144	0.0.0113
Mass flow rate in second evaporator($m_2^{''}$)	0.02882	0.0469	0.04138	0.03389	0.0542	0.04377	0.0405	0.05838
Mass flow rate in second compressor (kg/s)	0.8656	1.052	1.092	0.9339	1.237	1.059	0.9643	1.195
Mass flow rate in third evaporator (m_3) (kg/s)	0.1844	0.2337	0.2357	0.20	0.275	0.230	0.2133	0.2708
Mass flow rate in third evaporator($m_3^{'}$) (kg/s)	0.00813	0.00618	0.00617	0.006529	0.00843	0.02339	0.0082	0.0086
Mass flow rate in third evaporator ($m_3^{''}$) (kg/s)	0.1151	0.1953	0.1659	0.1324	0.2316	0.1725	0.1723	0.2536
Mass flow rate in third Compressor(m_{c3}) (kg/s)	1.173	1.488	1.50	1.273	1.752	1.464	1.358	1.725

This is due to that second law efficiency is computed by COP of Carnot at condenser and evaporator difference instead of difference between dead state temperature minus evaporator temperature. Similarly, by using R1224yd(Z), R1233zd(E) and R-1336mzz(Z), R-1243zf, R1225ye(Z) and R1234ze(E), the first law efficiency, second law efficiency and exergetic efficiency is much higher than using R1234yf. Similarly, by using R-1234yf, the compressor work (exergy of fuel in kW) is highest. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future. The thermodynamic performances of modified systems (system-4,5,6) have been compared and it was found that system-4 gives higher first law performance (COP) as compared to system-5 & 6, while system-5 also have nearly higher thermodynamic performances than system-6.

4. Conclusions

Energetic and exergetic analysis of two stage refrigeration system was carried out with different refrigerants and following conclusion and recommendation are presented below:

(i) R1234yf shows lowest thermodynamic performances among selected refrigerants.
(ii) Exergetic and energetic efficiency of R1234ze(Z) is highest among selected refrigerants.
(iii) Flash chamber responsible for lowest exergy destruction for all refrigerants taken under consideration. (iv)However the performance of R1233zd(E), R1336mzz(Z) and R1243zf is higher than R1234yf limited applications.
(iv) Although thermal performances of modified vapour compression refrigeration systems using R1234ze(Z), R1224yd(Z), R1233zd(E) and R1336mzz(Z) is higher than using R134a.
(v) Thermodynamic performances of modified vapour compression refrigeration systems using R1234ze(E) and R-1243zf and R1225ye(Z) is nearly similar with slightly less percentage difference and R1234yf has 3 to 4% lower thermodynamic performances. Therefore, R1234ze(Z), R1224yd(Z), are recommended for replacing R134a in high temperature applications.
(vi) R1243zf, R1234ze(E), and R1233zd(E) to be recommended for replacing R134a low temperature applications up to -30ºC.
(vii) R1234yf R1225ye(Z), R1233zd(E) and R1336mzz(Z) to be recommended for replacing R134a low temperature applications up to -50ºC.
(viii) R1225ye(Z), R1336mzz(Z) and R1233zd(E) to be recommended for replacing R134afor low temperature applications up to -75ºC.
(ix) R1225ye(Z) and R1336mzz(Z) to be recommended for replacing R134afor low temperature applications up to -100ºC.
(x) R1225ye(Z) and R1336mzz(Z) to be recommended for replacing R404a for low temperature applications up to -135ºC.
(xi) R1225ye(Z) and R1336mzz(Z) can be used for ultra-low temperature applications up to -155ºC.

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