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ORIGINAL ARTICLE

Comparison of six modified VCR systems at different evaporators temperatures using single and multiple compressors expansion valves using seven ultra-low GWP ecofriendly refrigerants

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Abstract

The effect of ecofriendly ultra-low GWP refrigerants used in the V.C refrigeration systems at different evaporators temperatures and different evaporator loads on thermal performances not been studied in detail so far in the literature. This papers mainly deals with the COP and exergy efficiency comparison of six modified VCR systems using ultra-low GWP refrigerants in multiple evaporators, multiple compressors of individual and multiple expansion valves types used in six types of VCR systems have been studied in detail and their thermal performances have been compared. Total exergy destruction is decreasing from system-1 to system-6 and rational exergy efficiency is increases. Maximum exergy destruction occurred in system-1 and in system-2 then decreases due to individual compressors and compound compression. It was found that by using sub-cooling, of systems, the exergy performance improvement was 1.133% to 2.54% and by using flash intercooler, the second law performance was improved 1.328 % to 1.414%. However, the best first and second law performances was observed at cooling load of first evaporator is 35KW, second evaporator of 70KW and third evaporator of 105 kW.

1. Introduction

Refrigerants are primarily employed in vapour compression-based equipment to absorb and transfer heat between space and the surrounding environment. Simple vapour compression system with four main parts: compressor, expansion valve, condenser, and evaporator. In this system, a single evaporator carries the entire cooling load at a single temperature; however, in many applications, such as large hotels, food processing facilities, and food storage facilities, food is stored in different compartments and at different temperatures. A multi-evaporator vapour compression refrigeration system is therefore required. The majority of these refrigerants are volatile and contain chemicals that have the potential to cause global warming or heat trapping, which can have an impact on the environment (GWP). In addition, a lot of these refrigerants have an effect on the ODP, or ozone layer. Most modern systems employ refrigerants with either no or very low ODP, including R134a and R410a. They still have a high GWP, though, and for certain refrigerants it can last up to 100 years. They will therefore likely be phased out of the market over the course of the next ten years. Based on the refrigerant selection criteria and their direct correlation to ozone layer depletion, the HVAC industry has gone through three major stages.

The first phase began with the development of vapour compression refrigeration cycle (VCC) systems and continued until the late 1920s, during which time the primary refrigerants utilized were primarily natural substances including methyl

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chloride, air, ether, ammonia, carbon dioxide, hydrocarbons, Sulphur dioxide, and chloroethene. Subsequently, the industry changed towards the widespread use of halogenated chemicals known as chlorofluorocarbons (CFCs) after freon was invented in 1930. In comparison to the earlier refrigerants, they offered remedies for toxicity, flammability, and odour, and they were advertised as a safer and more effective choice at the time, prior to the later revelation that CFCs pose a serious hazard to human life through. When the effects of CFCs on the environment were realized half a century after they were first introduced, the world decided to phase them out via the 1987 Montreal Protocol. The Document, published in 2017 by the Montreal Protocol, outlined a mandatory phase-out schedule for CFCs. Hydrofluorocarbons (HFCs) were introduced as a substitute for CFCs in this collaborative endeavors. Due to its GWP, some limitations on the use of HCFCs, also known as Freons, were proposed in an effort to lessen the environmental impact of refrigerants. Furthermore, a framework for limiting global warming and maintaining it below 2°C was established by the 2015 Paris Agreement. 2016 saw the adoption of the Kigali amendment to the Montreal Protocol, which called for the phase-out of high-GWP HFCs and an 85% decrease in GWP-weighted products in industrialized nations by 2036, with later phase-down dates for other nations. Few binary mixtures consisting of pure refrigerants, R134a, R1234yf, R1234ze(E), R32, R227ea, and R152a, were unable to identify a blend that worked better than R134a [3]. Hydro flouroolefins (HFOs) are the most promising refrigerant substitutes currently available. Compared to HFCs, these refrigerants have a much shorter atmospheric lifetime but have the potential to cause global warming. While some of these refrigerants are combustible and hazardous, HFO-1234yf is hard to light and has an unstable flame. It is therefore frequently used in car air conditioning systems and is anticipated to soon take the place of R-134a refrigerant in this specific application. HFO-1336mzz(Z) and HFO-1234ze(E) are better suited for chiller applications since they are less poisonous and non-flammable. The efficiency of a vertical refrigerator at measured ambient temperatures was investigated. [4] The HFO-1234ze(E) refrigerant to replace R134a due to 6% energy improvement was observed.

A new class of refrigerants known as hydro chlorofluoro olefins (HCFOs) combines chlorine and fluorine and possesses a negligible ODP and a comparatively low GWP. HCFOs have been marketed as very short atmospheric lifespan refrigerants that are appropriate for chillers. HCFO-1233zd(E), with an ODP of less than 0.0004. The refrigerant HCFO-1224yz(Z) is another one. The thermodynamic performances of HCFO-1224yz(Z) are marginally better than those of HCFO-1233zd(E) and marginally worse than those of HFO-1336mzz(Z). An effective technique for identifying irreversibilities that have developed in both the system's components and overall structure is the exergy analysis [5]. One of the main concerns for protecting our environment is ozone depletion and global warming. eight environmentally friendly refrigerants on two types of multiple-stage vapour compression refrigerators: one with a flash intercooler and individual throttle valves (system-1) and another with a flash intercooler and multiple throttle valves (system-2) [6]. The analysis is done using both first- and second-law methods [7]. For the eight ecofriendly refrigerants, the first law efficiency (COP) and energy efficiency of modified VCR systems using multiple evaporators with compound compression, flash intercooler and individual throttle valves (system-1)] and multiple evaporators with compound compression, flash intercooler and multiple throttle valves (system-2) were compared[8] using detailed energy -exergy evaluations of VCR systems using ecofriendly HFO, HCFO, HCFC and HFC refrigerants and found higher irreversibility's and the first law efficiency (COP) and energy efficiency are lower of VCR system using multiple evaporators with compound compression, flash intercooler and individual throttle valves than multiple evaporators with compound compression, flash intercooler and multiple throttle valves[9]. The eco-friendly HFC125 refrigerant proved the lowest COP (energetic efficiency), exergetic efficiency (second law efficiency), and higher irreversibilities in terms of energy destruction ratio (EDR) [10]. Hydrocarbon (HC 600a) and natural refrigerant ammonia (R717) showed superior energetic and exergetic performances when compared to other carefully for chosen eco-friendly refrigerants for both systems. While the environmentally friendly R717 refrigerant is hazardous by nature and should only be used in specific applications, the hydrocarbon R600 refrigerant performs marginally worse than R717 and 2-3% better than R134a and is combustible by nature, thus it can be used without the need for safety precautions. R134a can therefore be applied in real-world scenarios. Furthermore, R134A is widely accessible. R1234yf (GWP four with no potential to deplete the ozone layer) performs well [11]. The change in the evaporator and condenser temperatures of a two-stage vapour compression refrigeration plant were carried out by several investigators using R22 have a significant impact on the irreversibility of the plant and found that the condenser and evaporator's operating conditions be optimized [12]. The impact of condensing and evaporating temperature on the vapour compression refrigeration cycle in terms of pressure losses, COP, second law efficiency, and exergy losses were investigated by using an exergy analysis approach [13]. Variations in the condenser's temperature likewise have little effect on the compressor's and expansion valve's energy losses. Additionally, while the system's overall energy losses reduce as the temperature of the evaporator and condenser rises, first law and energy efficiency also rise. The thermal and energy efficiency of a residential refrigerator utilizing R513A. was evaluated,[14]. The results showed that a refrigerator operating on R513A uses approximately 9% less energy than one operating on R134a and offers the optimal conditions for food preservation. As a result, considerable adjustments have to be made by the refrigeration sector in order to produce and utilized ecologically kind refrigerants. A substitute for R134a, synthetic fluids like HFOs has been thought to be a feasible option. The experiment was conducted for new refrigerant mix RGT2 (R134a/R1234yf/R161, 54%/43%/3% wt%) in a heat pump system and performance was evaluated both conceptually and empirically. The results showed that although though RGT2 has a 3.8% lower COP, it can cool just as well as R134a. When replacing R134a in a commercial refrigerator with different low-GWP refrigerants [15]. The studies have been carried out for using hydrocarbons and discovered results showed that R290 and R1270 offer the biggest energy savings while R1234yf used in the system consumed more energy than using R134a [16].

Detailed energy and exergy analysis of multiple evaporators at varying temperatures with a single compressor and expansion valve using liquid vapour heat exchanger vapour compression refrigeration systems were conducted and the numerical calculations have been carried out. The performance parameters have been evaluated ecofriendly refrigerants by using R507a, R125, R134a, R290, R600, R600a, R1234ze, R1234yf, R410a, R407c, R707, R404a, and R152a. It was found that employing liquid vapour heat exchangers in vapour compression refrigeration systems increased first law and second law efficiency by 20%. Additionally, it was noted that both systems work better while using R717, however the system mentioned above may also use R600 and R152a, which almost match the same numbers with a 5% accuracy. Safety precautions must be taken while utilizing low GWP refrigerants (like R152a) and hydrocarbons (like R600, R290, and R600a) because they have flammable issues. Because R134a has marginally lower thermal performance than R152a, a refrigerant that is not commonly utilised for home and industrial applications, it is thus advised for practical and commercial uses. HFO refrigerants R1234yf and R1234ze(E) were first classified as non-flammable combinations and were intended to replace R134a [17].

The performance of R513A and R134a in a home refrigerator is carried out to establish the proper charge for R513A. The refrigerator used 3.5% less energy when utilizing R513A than when using R134a, according to the findings [18]. The studies using R513A, R516A, and R1234yf in a heat pump under various operating conditions and found that R513A performed similarly to R134a, whereas R516A using refrigeration systems needs to be modified to perform [19] Similarly to R134a. R1234yf is a pure HFO that is widely studied due to its low GWP < 1. The other study also indicating that R516A behaved fairly similarly to R134a in experiments [20], in the system. The ultralow GWP ecofriendly HFO1234ze(E) refrigerant can be used as long-term alternatives to HFC134a. However, R515A, R513A and R450A can be considered a short-term alternative due to non-flammable nature of R513A similar to HFC134a.However A2L-classified refrigerants R1234ze(E). is suitable for use in domestic refrigeration due to similar thermophysical characteristics to R134a [21].

There have been efforts made to reduce the harm caused by the use of HFCs because their use was expected to contribute 2% of greenhouse gas emissions in 2015 and might account for 20% by 2050. Mota-Babiloni et al. [22] found performance differences between R513A and R134a by using internal heat exchangers. Mishra ecofriendly HFO+HFC blends such as R513A, R515A, and R450A can, respectively, replace HFC134A, HFC-404A, and HFC-410A are used [22]. Thermodynamic performances. The environmental properties of few ecofriendly refrigerants were shown in table-1.

Table-1: GWP and ODP of eco-friendly HFOs and HCFOs refrigerants in vapour compression refrigeration systems using multiple evaporators at different temperatures with single/multiple compressors of individual /multiple expansion valves

S. No	Low GWP refrigerants	*GWP*	*ODP*
1	HCFO 1233zd(E)	6	0.00034
2	HCFO 1224yd(Z)	1	0.00023
3	HFO 1336mzz(Z)	2	0
4	HFO 1243zf	9	0
5	HFO 1234ze(E)	7	0
6	HFO 1225ye(Z)	14	0
7	HFO 1234yf	4	0

2. Results and discussion

The following six vapour compression refrigeration systems have been considered for comparing thermodynamic performances shown in Table-2 respectively.

Table-2: Types of vapour compression refrigeration systems

Systems	
System-1	Modified VCR systems using multiple evaporators at different temperatures with single compressor of individual expansion valves
System-2	Modified VCR systems using multiple evaporators at different temperatures with single compressor of multiple expansion valves
System-3	Modified VCR systems using multiple evaporators at different temperatures with compound compression and individual expansion valves
System-4	Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves
System-5	Modified VCR systems using multiple evaporators at different temperatures with compound compression with individual expansion valves with flash chambers
System-6	Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves with flash chambers

Similarly following input data have been considered for evaluating thermodynamic performances are shown in table-3 and table-4 respectively.

Table-3 Different evaporator loads used in VCRS using ultra-low GWP eco-friendly HFOs and HCFOs refrigerants in vapour compression refrigeration systems using multiple evaporators at different temperatures with single/multiple compressors of individual /multiple expansion valves.

S. No.	Evaporator load Parameters	“kW”
1	First Evaporator Load (Q_Eva1)	70
2	Second Evaporator Load (Q_Eva2)	105
3	Third Evaporator Load (Q_Eva3)	35

Table-4 Different evaporator used in VCRS using ultra-low GWP eco-friendly HFOs and HCFOs refrigerants in vapour compression refrigeration systems using multiple evaporators at different temperatures with single/multiple compressors of individual /multiple expansion valves

S. No.	Evaporator temperatures	"K"
1	First Evaporator temperature (T_Eva1)	263
2	Second Evaporator temperature (T_Eva2)	273
3	Third Evaporator temperature (T_Eva3)	278

The ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly refrigerants at 100% isentropic efficiency of all three compressors and thermal performances of all systems have been compared and shown in Tables-6(a) to Table-6(f) respectively. It was found that highest first and second law performances all VCR systems were observed using HCFO-1233ze(E) and lowest was observed by using HFO-1234yf. Thermodynamic ideal performances of all six systems using HCFO-1224yd(Z) is slightly lower but higher than HFO-1336mzz(Z). Amongst selected HFO refrigerants HFO-1336mzz(Z) gives better ideal thermodynamic performances than other ecofriendly ultralow GWP refrigerants. The electrical power consumption for running system (exergy of fuel) is decreasing and becomes lowest for system-6 and higher for system-1. Similarly, coefficient of performance is also increasing from system-1 to system-6.

Table-5(a) Detailed ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1233zd(E)

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	4.329	25.85	9.511	35.37	1.16	71.83	28.27	48.51	15.19	0.3132
System-2	4.672	25.69	15.36	9.66	1.272	46.85	53.15	44.95	17.24	0.3724
System-3	5.757	30.27	11.55	9.32	1.579	52.72	0.4728	36.48	17.24	0.4728
System-4	5.993	31.33	18.27	5.805	1.632	57.04	0.4241	35.04	17.24	0.4921
System-5	5.992	31.33	18.28	5.813	1.634	55.99	0.4401	35.05	17.24	0.4921
System-6	5.995	30.95	18.21	5.814	1.635	54.965	0.45035	35.005	17.24	0.4925

Table-5(b) Detailed ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1224yd(Z)

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	4.271	25.4	9.01	38.12	1.26	73.78	26.27	49.17	15.19	0.3010
System-2	4.64	25.27	15.37	10.36	1.40	46.9	53.1	45.26	17.24	0.3715
System-3	5.716	29.92	11.44	9.965	1.735	53.06	0.4694	36.74	17.24	0.4867
System-4	5.965	31.03	18.52	6.246	1.799	57.57	0.4243	35.2	17.24	0.4921
System-5	5.965	31.03	18.52	6.246	1.799	56.43	0.4357	35.2	17.24	0.4899
System-6	5.994	30.97	18.22	5.816	1.636	56.642	0.4336	35.0	17.24	0.4920

Table-5(c) Detailed ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and xergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1336mzz(Z)

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporator (%)	Exergy destruction in throttle valves (%)	Exergy destructio n in sub cooler	Total exergy destructio n (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	4.224	25.04	9.64	40.14	1.19	75.92	24.08	49.17	17.24	0.3004
System-2	4.611	24.95	16.55	10.6	1.399	47.99	52.01	45.55	17.24	0.3599
System-3	5.685	29.65	11.38	10.57	1.729	53.32	0.4668	36.94	17.24	0.4668
System-4	5.953	30.83	18.96	6.569	1.807	58.16	0.4184	35.28	17.24	0.4567
System-5	5.955	30.84	18.95	6.544	1.799	56.97	0.4303	35.28	17.24	0.4890
System-6	5.992	30.98	18.24	5.818	1.637	56.675	0.4333	35.03	17.24	0.4918

Table-5(d) Detailed ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1243zf

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	3.963	24.14	6.431	46.93	1.29	78.79	0.2121	52.99	16.96	0.3201
System-2	4.378	23.99	13.9	13.84	1.961	46.26	53.79	47.97	17.24	0.3762
System-3	5.425	28.07	12.44	12.47	2.459	55.44	0.4456	38.71	17.24	0.4445
System-4	5.696	29.28	20.26	8.328	2.552	60.43	0.3957	35.28	17.24	0.4677
System-5	5.694	29.25	20.28	8.36	2.563	58.84	41.16	36.88	17.24	0.4676
System-6	5.990	30.93	18.23	5.817	2.636	57.613	0.42387	35.03	17.24	0.4918

Table-5(e) Detailed ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultralow GWP ecofriendly HCFO-1234ze(E)

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	4.055	24.42	6.034	47.68	1.572	79.63	0.2037	51.75	16.43	0.3173
System-2	4.498	24.31	13.66	13.60	1.982	46.23	53.77	46.68	17.24	0.3764
System-3	5.546	28.72	10.56	12.51	2.46	54.52	0.4548	37.87	17.24	0.4554
System-4	5.851	30.02	18.68	8.176	2.578	59.49	0.4051		17.24	0.4468
System-5	5.841	30.02	18.65	8.16	2.572	57.92	0.4208	35.95	17.24	0.4796
System-6	5.994	30.91	18.22	5.816	2.635	57.58	0.4242	35.03	17.24	0.4918

Table-5(f) Detailed ideal thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HFO-1225ye(Z)

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	4.001	24.17	5.903	48.9	1.587	79.99	0.2001	52.49	16.66	0.3175
System-2	4.452	24.05	13.66	14.05	2.058	46.28	0.5372	47.17	17.24	0.3761
System-3	5.503	28.41	11.01	12.83	2.566	54.81	0.4519	38.15	17.24	0.4519
System-4	5.794	29.68	19.15	8.463	2.679	59.97	0.4003	36.24	17.24	0.4424
System-5	5.794	29.68	19.15	8.469	2.680	58.27	0.4173	36.25	17.24	0.4758
System-6	5.980	30.89	18.18	5.815	2.637	56.612	0.424	35.03	17.24	0.4918

Table-5(g) Exergy destruction of components in the modified VCR systems using ultra low GWP ecofriendly HFO-1234yf

Modified VCR system	COP	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy of product "kW"	Exergy Efficiency
System-1	3.842	23.31	9.511	55.37	2.024	88.01	0.1399	54.66	16.91	0.3093
System-2	4.341	23.21	13.74	15.97	2.424	46.86	53.14	48.37	17.24	0.3688
System-3	5.372	27.28	10.75	14.63	3.021	54.93	0.45.07	38.73	17.24	0.4411
System-4	5.693	28.86	19.64	9.816	3.179	61.49	0.38505	36.89	17.24	0.3850
System-5	5.694	28.87	19.64	9.801	3.174	61.485	0.38515	36.25	17.24	0.4758
System-6	5.695	28.88	19.65	9.80	3.049	57.27	0.4273	36.24	17.24	0.4760

2.1 Actual performances

The actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly refrigerants at 80% isentropic efficiency of all three compressors and thermal performances of all systems have been compared and shown in Tables-6(a) to Table-6(f) respectively. It was found that highest first and second law performances all VCR systems were observed using HCFO-1233ze(E) and lowest was observed by using HFO-1234yf. Thermodynamic actual performances of all six systems using HCFO-1224yd(Z) is slightly lower but higher than HFO-1336mzz(Z). Amongst selected HFO refrigerants HFO-1336mzz(Z) gives better thermodynamic performances than other ecofriendly ultralow GWP refrigerants. The electrical power consumption for running system (exergy of fuel) is decreasing and becomes lowest for system-6 and higher for system-1. Similarly, coefficient of performance is also increasing from system -1 to system-6.and power consumption.

Table-6(a) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1233zd(E)

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel “kW”	Exergy Efficiency
System-1	3.463	18.19	22.49	7.609	28.29	1.02	77.58	0.2242	60.64	0.2506
System-2	3.737	18.31	21.2	6.02	26.14	1.018	72.69	0.2731	56.57	0.2980
System-3	4.572	19.46	25.1	9.182	7.444	1.265	61.17	0.3883	45.93	0.3755
System-4	4.794	18.88	26.19	14.62	4.644	1.306	63.63	0.3637	43.8	0.3937
System-5	4.764	15.68	25.96	14.55	4.652	1.309	65.14	0.3486	44.08	0.3912
System-6	4.775	15.67	25.91	15.02	7.11	1.404	65.11	0.3489	43.99	0.3919

Table-6(b) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1224yd(Z)

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel “kW”	Exergy Efficiency
System-1	3.416	18.43	21.89	7.204	30.50	1.03	79.02	0.20093	61.47	0.2498
System-2	3.712	18.53	21.6	6.21	26.17	1.329	73.84	0.2616	56.57	0.2972
System-3	4.539	19.53	24.74	9.087	7.959	1.389	61.32	0.3868	46.25	0.3727
System-4	4.772	18.99	25.83	14.82	4.997	1.439	66.08	0.3392	44.01	0.3919
System-5	4.743	15.68	25.96	14.55	4.999	1.43	65.5	0.3450	44.28	0.3895
System-6	4.767	15.69	25.93	15.04	7.12	1.44	65.22	0.3478	44.273	0.3894

Table-6(c) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1336mzz(Z)

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel in “kW”	Exergy Efficiency
System-1	3.379	18.76	21.27	7.712	32.11	1.04	80.89	0.1911	62.15	0.2403
System-2	3.689	18.87	21.1	6.26	27.97	1.379	75.579	0.2442	56.93	0.2879
System-3	4.514	19.56	24.54	9.033	8.442	1.385	62.96	0.3704	46.53	0.3536
System-4	4.762	19.04	25.62	15.17	5.255	1.445	66.53	0.3347	44.09	0.3919
System-5	4.734	19.48	25.49	15.09	5.237	1.44	65.94	0.3406	44.36	0.3888
System-6	4.765	19.40	25.41	14.87	5.233	1.430	64.913	0.351	44.25	0.3896

Table-6(d) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra-low GWP ecofriendly HCFO-1243zf

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel “kW”	Exergy Efficiency
System-1	3.17	18.22	21.09	5.145	37.54	1.010	83.01	0.1699	66.24	0.2380
System-2	3.502	18.29	20.9	11.12	28.98	1.569	80.86	0.1914	59.96	0.3010

System-3	4.306	19.36	23.43	9.875	9.962	1.97	62.62	0.3738	48.77	0.3536
System-4	4.557	18.73	24.69	16.21	6.663	2.042	68.34	0.3166	46.09	0.3742
System-5	4.526	19.27	24.40	16.14	6.691	2.052	67.49	0.3251	46.4	0.3717
System-6	4.567	18.69	24.53	16.04	6.10	2.040	67.40	0.3460	44.273	0.3894

Table-6(e) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra low GWP ecofriendly HCFO-1234ze(E)

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency	Exergy of fuel "kW"	Exergy Efficiency
System-1	3.244	18.49	21.05	4.827	38.14	1.06	83.58	0.1642	64.73	0.2353
System-2	3.599	18.57	20.88	10.93	28.82	1.585	80.785	0.19215	58.3	~~0.3010~~
System-3	4.402	19.71	23.79	8.381	9.993	1.972	63.85	0.3615	47.7	0.3615
System-4	4.681	18.99	25.06	14.94	6.541	2.062	67.59	0.3241	44.86	0.3844
System-5	4.643	19.59	24.85	14.94	6.53	2.06	66.75	0.3325	45.23	0.3813
System-6	4.715	18.49	24.13	15.11	6.13	2.015	65.875	0.34125	44.27	0.3896

Table-6(f) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra low GWP ecofriendly HFO-1225ye(Z)

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency (%)	Exergy of Fuel "kW"	Second law Efficiency (%)
System-1	3.201	18.47	20.87	4.723	39.12	1.06	84.18	0.1582	65.61	0.2540
System-2	3.562	18.54	20.71	10.93	29.12	1.647	80.94	0.1906	58.96	0.3009
System-3	4.368	19.51	23.56	8.741	10.25	2.055	64.12	0.3588	48.06	0.3587
System-4	4.635	18.95	24.8	15.32	6.77	2.143	67.98	0.3202	45.31	0.3589
System-5	4.606	19.42	24.61	15.25	6.778	2.146	67.04	0.3296	45.6	0.3641
System-6	4.569	18.62	24.52	15.11	6.13	2.044	66.424	0.3360	44.26	0.3895

Table-6(g) Detailed actual thermodynamic performances (first law efficiency (COP), Exergy efficiency and Exergy destruction of components in the modified VCR systems using ultra low GWP ecofriendly HFO-1234yf

Modified VCR system	COP	Exergy destruction in compressor (%)	Exergy destruction in condenser (%)	Exergy destruction in evaporators (%)	Exergy destruction in throttle valves (%)	Exergy destruction in sub cooler (%)	Total exergy destruction (%)	Rational Exergy Efficiency (%)	Exergy of fuel "kW"	Exergy Efficiency
System-1	3.073	18.61	20.04	4.116	44.45	1.09	88.29	0.1171	68.33	0.2474
System-2	3.473	18.67	19.85	10.99	30.42	1.94	81.87	0.1813	60.49	0.2951
System-3	4.263	19.56	22.79	8.531	11.69	2.329	64.67	0.3533	49.26	0.3501
System-4	4.554	19.01	24.07	15.71	7.853	2.543	69.20	0.3080	46.11	0.3740
System-5	4.526	19.45	23.93	15.63	7.844	2.541	68.04	0.3196	46.4	0.3717
System-6	4.532	19.31	23.34	15.41	7.612	2.340	68.012	0.3199	46.36	0.3719

3. Conclusions

The following conclusions were drawn.

- Highest first and second law performances were observed in all (six) modified VCR systems by using ultra-low GWP ecofriendly HCFO-1233zd(E) refrigerant.
- Lowest first and second law (thermodynamic) performances were observed in all (six) modified VCR systems by using ultra-low GWP ecofriendly HFO-1234yf.
- First and second law (energy-exergy) performances in all (six) modified VCR systems by using ultra-low GWP ecofriendly HCFO-1224yd(Z) refrigerant is slightly lower than HCFO-1233zd(E)but higher than other five ecofriendly HFO refrigerants (HFO-1336mzz(Z), R-1234ze(E), R1225ye(Z), R1243zf.
- First and second law (energy-exergy) performances in all (six) modified VCR systems by using ultra-low GWP ecofriendly HFO-1336mzz(Z) refrigerant is lower than HCFO-1233zd(E) and HCFO-1224yd(Z) but higher than

- other five ecofriendly HFO refrigerants (R-1234ze(E), R1225ye(Z), R1243zf.
- The electrical power consumption for running system (exergy of fuel) is decreasing and becomes lowest for system-6 and higher for system-1.
- Coefficient of performance (COP) is also increasing from system -1 to system-6.
- In the actual analysis, for running compressor/all compressors at 80% of efficiency, the maximum exergy destruction was found in condenser component in the all (six) systems.
- By subcooling of systems, the performance improvement was 1.133% to 2.54% and
- Maximum exergy destruction occurred in system-1 and in system-2 then decreases due to individual compressors and compound compression.
- By using Flash intercooler, the second law performance was improved 1.328 % to 1.414%
- Total exergy destruction is decreasing from system-1 to system-6 and rational exergy efficiency is increases.

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