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ORIGINAL ARTICLE

Thermodynamic static and dynamic performances of VCRS using low GWP blends of HFC+HFO refrigerants in higher temperature cycle using blends of HFC+HFO refrigerants in low GWP refrigerant in low temperature cycle

R. S. Mishra

Department of Mechanical Engineering, Delhi Technological University Delhi, India

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Abstract

In this paper, comparison of static and dynamic thermodynamic energy-exergy performances of eight optimal combinations of cascaded vapor compression refrigeration system for the ultra-low applications using ecofriendly low global warming potential GWP blends of HFC+HFO refrigerants in higher temperature cycle in the temperature range of 50° C to -30° C and also using blends of HFC+HFO refrigerants in low GWP in low temperature cycle between (-30° C to -70° C) have been analyzed. It was found that the optimal Cascaded vapor compression refrigeration system 44 using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle gives best (optimum) thermodynamic first law energy performance (COP) and second law (exergetic efficiency) performances with lowest electrical energy consumption. in the dynamic performances it was found that by increasing temperature overlapping, decreases the thermodynamic performances of cascaded refrigeration systems.

1. Introduction

In current decades many countries have been taken more consideration to environmental pollution caused by CFCs. Burning fossil fuels because vapor compression refrigeration system based applications make use of refrigerants which are responsible for greenhouse gases, global warming and ozone layer depletion. Montreal protocol was signed on the issue of substances that are responsible for depleting Ozone layer and discovered how much consumption and production of ozone depletion substances took place during certain time period for both developed and developing countries. Another protocol named as Kyoto aimed to control emission of greenhouse gases in 1997. The relationship between ozone depletion potential and global warming potential is the major concern in the field of GRT (green refrigeration technology) so Kyoto proposed new refrigerants having lower value of ODP and GWP. Internationally a program being pursued to phase out refrigerants having high chlorine content for the sake of global environmental problems. Due to presence of high chlorine content, high global warming potential and ozone depletion potential after 90's CFC and HCFC refrigerants have been restricted. Thus, HFC refrigerants are used nowadays, showing much lower global warming potential value, but still high with respect to non-fluorine refrigerants. Lots of research work has been done for replacing "old" refrigerants with "new" refrigerants [1]. The thermodynamic performances of systems based on vapor compression refrigeration technology can be improved by following methods.

Corresponding author: R.S. Mishra
Email Address: hod.mechanical.rsm@dtu.ac.in
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The performance of refrigerator is evaluated in term of COP which is the ratio of refrigeration effect to the net work input given to the system. The COP of vapor compression refrigeration system (VCRS) can be improved either by increasing refrigeration effect or by reducing work input given to the system.

We know that the throttling process in VCR is an irreversible expansion process. The expansion process is one of the main factors responsible for exergy loss in cycle performance because of entering the portion of the refrigerant flashing to vapor in the evaporator which will not only reduce the cooling capacity but also increase the size of the evaporator. This problem can be eliminated by adopting multi-stage expansion with a flash chamber where the flash vapors are removed after each stage of expansion as a consequence there will be an increase in cooling capacity and reduce the size of the evaporator. The compressor work (input electrical energy consumption) can also be reduced by replacing multi-stage compression or compound compression with single-stage compression. Similarly, the refrigeration effect can also be increased by passing the refrigerant through the sub-cooler after the condenser to the evaporator [2-3]. Nikolaidis and Probert [4] studied analytically that change in evaporator and condenser temperatures of two-stage vapor compression refrigeration plant using R22 add considerable effect on plant irreversibility. They suggested that there is a need for optimizing the conditions imposed upon the condenser and evaporator. Getu and Bansal [5] had optimized the design and operating parameters of condensing temperature, subcooling 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 the same system. Mishra [5] described thermodynamic analysis of cascade refrigeration system with huge refrigerant sinking CFC, HCFC, HFC, HFC, and HFO refrigerants, etc., and optimizations conducted for such refrigerants. A huge number of refrigerants have been examined in a cascade system for determining the appropriate combination of refrigerants in high temperature and low-temperature cycle circuits of refrigerants however the trends show that the HFO refrigerants a natural refrigerant is gaining more importance due to environmental conditions few natural refrigerants. [3].

Exergy analysis is a useful way for determining the real thermodynamic losses and optimizing environmental and economic performance in the systems such as vapor compression refrigeration systems. Alptunganbaba et.al.[7] carried out exergy analysis of a two evaporator vapor compression refrigeration system using R1234yf, R1234ze, and R134a as refrigerants and computed the effect of evaporator and condenser temperatures on the exergy destruction and exergy efficiency of the system Adrián Mota-Babiloni [8] studied the feasibility of R454C and R455A, refrigerants, in vapor compression refrigeration systems as alternatives to R404A and found that the R454C and R455A will be the most viable low GWP options to perform a direct replacement of R404A. This paper mainly deals with the static and dynamic thermodynamic energy& exergy performances of eight optimal cascaded vapor compression using HFO+HFC blends.

2. Results and Discussion

In this paper, two types of thermodynamic energy and exergy performances for different optimal combination of cascaded vapor compression refrigeration systems have been computed. The numerical computation was carried out for optimal conditions explained in details. However dynamic thermodynamic performances have been computed with varying HTC evaporator temperature from -0ºC to -30ºC), the HTC condenser temperature variation from 40ºC to 60ºC, LTC evaporator temperature from -50ºC to -70ºC and temperature overlapiping from 0ºC to 15º C.

2.1 Static thermodynamic performances

For finding static thermodynamic (energy and exergetic) performances of cascaded vapor compression refrigeration systems the following eight optimal cascaded vapor compression refrigeration systems have been considered for numerical computations.

System-1: Cascaded vapor compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}=50ºC, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , T_{Eva_LTC}=-90ºC, Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%, Compressor $efficiency\_{LTC}$=80%,

System- 2: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R513A refrigerants in higher temperature cycle using ecofriendly R452B low GWP refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}= 50ºC, T_ambient = 25ºC, T_{Eva_HTC}=-30ºC, T_{Eva_LTC}=-90ºC, Temperature overlapping =10, Compressor $efficiency\_{HTC}$ =80%, Compressor $efficiency\_{LTC}$ = 80%,

System-3: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}=50ºC, T_ambient=25ºC, T_{Eva_HTC}=-30ºC, T_{Eva_LTC}=-90ºC, Temperature overlapping=10, Compressor $efficiency\_{HTC}$ = 80%, Compressor $efficiency\_{LTC}$=80%,

System-4: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R452C refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, T$_{_cond}$=50ºC, T_ambient= 25ºC, T$_{_Eva_HTC}$=-30ºC, T$_{_Eva_LTC}$=-90ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,

System-5: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, T$_{_cond}$=50ºC, T_ambient= 25ºC, T$_{_Eva_HTC}$=-30ºC, T$_{_Eva_LTC}$=-90ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,

System-6: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R449A refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, T$_{_cond}$=50ºC, T_ambient= 25ºC, T$_{_Eva_HTC}$=-30ºC, T$_{_Eva_LTC}$=-90ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,

System-7: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, T$_{_cond}$=50ºC, T_ambient= 25ºC, T$_{_Eva_HTC}$=-30ºC, T$_{_Eva_LTC}$=-90ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,

System-8: Cascaded thermodynamic performances of vapor compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, T$_{_cond}$=50ºC, T_ambient =25ºC, T$_{_Eva_HTC}$=-30ºC, T$_{_Eva_LTC}$=-90ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%.

Table-1(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454C refrigerants in higher temperature cycle using low GWP HFC+HFO blends in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, T$_{_cond}$=50ºC, T_ambient=25ºC, T$_{_Eva_HTC}$=0ºC , T$_{_Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,

Cascaded VCRS	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
HFC +HFO Blends in HTC	R450A	R513A	R454B	R454C	R448A	R449A	R452A	R452B
HFC +HFO Blends in LTC	R513a	R452b	R513a	R513a	R513A	R513A	R513A	R513A
First Law Cascaded Efficiency COP$_{_ Cascade}$	0.7711	0.7811	0.7544	0.7106	0.7394	0.7288	0.7606	0.7031
Exergy Destruction Ratio(EDR$_{_Cascade}$)	1.773	1.738	1.835	2.009	1.892	1.934	1.812	2.042
Cascaded Exergetic Efficiency	0.3606	0.3653	0.3528	0.3323	0.3458	0.3408	0.3557	0.3288
Exergy of Fuel "kW"	45.61	45.02	46.62	49.49	47.56	48.25	46.24	50.02
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5276	0.5761	0.3552	0.4979	0.4717	0.5007	0.3510	0.7087
LTC Mass flow Rate (Kg/sec)	0.2992	0.1672	0.2992	0.2992	0.2992	0.2992	0.2992	0.2992
W$_{_comp\ _HTC}$"kW"	19.65	19.64	20.66	23.53	21.60	22.29	20.28	24.06
W$_{_comp_LTC}$ "kW"	25.96	25.39	25.96	25.96	25.96	25.96	25.96	25.96
Q$_{_Cond_HTC}$ "kW"	80.77	80.19	81.78	84.65	82.73	83.42	81.40	85.19
Q$_{_Cond_LTC}$ "kW"	61.12	60.55	61.12	61.12	61.12	61.12	61.12	61.12
Q$_{_Eva_HTC}$ "kW"	61.12	48.67	61.12	61.12	61.12	61.12	61.12	61.12
Q$_{_Eva_LTC}$ "kW"	35.16	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	1.355	1.385	1.355	1.355	1.355	1.355	1.355	1.355
First Law HTC Efficiency COP$_{_ HTC}$	3.111	3.084	2.959	2.598	2.660	2.660	3.014	2.54
HTC Exergy Destruction Ratio(EDR$_{_HTC}$)	2.502	2.543	2.693	3.206	2.861	2.985	2.625	3.301
HTC Exergetic Efficiency	0.2847	0.2822	0.2708	0.2378	0.2590	0.2590	0.2759	0.2325
HTC Exergy of Fuel "kW"	19.65	19.64	20.66	23.63	21.60	22.29	20.28	24.06
HTC Exergy of Product "kW"	5.594	5.542	5.594	5.594	5.594	5.594	5.594	5.594

Table-1(a) shows the comparison of static thermodynamic performances of cascaded vapor compression refrigeration systems using eight different combinations of HFC +HFO Blends in high temperature cycle at -30ºC in HTC evaporator and two different HFC +HFO Blends (R513a and R R452a) in low temperature cycle and it was found that optimal cascaded vapor compression refrigeration system-2 using R454B in high temperature cycle and R513A in low temperature cycle gives highest first law efficiency and exergetic efficiency with lower power consumption in the both compressors along with lowest system exergy destruction ratio. Similar trends were observed in the thermodynamic system first law (energy) performance (COP$_{_cascade}$) and exergetic performance at evaporator temperature -5ºC in table-1(b) and at HTC evaporator temperature of -30ºC and LTC evaporator temperature of -70ºC as shown in table-1(C) respectively.

Table-1(b) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454C refrigerants in higher temperature cycle using low GWP HFC+HFO blends in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T$_{cond}$=50ºC, T_ambient=25ºC, T$_{Eva_HTC}$=-5ºC, T$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,

Cascaded VCRS	System:1	System 2	System 3	System: 4	System 5	System 6	System 7	System: 8
HFC +HFO Blends in HTC	R450A	R513A	R454B	R454C	R448A	R449A	R452A	R452B
HFC +HFO Blends in LTC	R513a	R452b	R513a	R513a	R513A	R513A	R513A	R513A
First Law Cascaded Efficiency COP$_{Cascade}$	0.7805	0.7827	0.76498	0.7143	0.7482	0.7358	0.7723	0.7637
Exergy Destruction Ratio(EDR$_{Cascade}$)	1.740	1.732	1.796	1.985	1.858	1.906	1.762	2.039
Cascaded Exergetic Efficiency	0.3650	0.3660	0.3577	0.3350	0.3499	0.3441	0.3612	0.3291
Exergy of Fuel "kW"	45.06	44.93	45.97	49.10	47.0	47.0	45.54	49.97
Exergy of Product "kW"	16.46	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5201	0.5708	0.3436	0.5203	0.4609	0.4894	0.3395	0.6990
LTC Mass flow Rate (Kg/sec)	0.283	0.1608	0.2830	0.2830	0.2830	0.2830	0.2830	0.2830
W$_{comp_HTC}$ "kW"	21.71	21.87	22.63	2575	23.66	24.45	22.19	26.63
W$_{comp_LTC}$ "kW"	23.35	23.07	23.35	23.35	23.35	23.35	23.35	23.35
Q$_{Cond_HTC}$ "kW"	80.23	80.10	81.14	84.26	82.17	82.96	80.7	85.14
Q$_{Cond_LTC}$ "kW"	58.51	58.51	58.51	58.51	58.51	58.51	58.51	58.51
Q$_{Eva_HTC}$ "kW"	48.39	58.51	58.51	58.51	48.39	48.39	58.51	58.51
Q$_{Eva_LTC}$ "kW"	35.16	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	1.506	1.506	1.506	1.506	1.506	1.506	1.506	1.506
First Law HTC Efficiency COP$_{HTC}$	2.695	2.663	2.586	2.272	2.272	2.473	2.637	2.197
HTC Exergy Destruction Ratio(EDR$_{HTC}$)	2.317	2.356	2.457	2.934	2.934	2.614	2.390	3.068
HTC Exergetic Efficiency	0.3015	0.2980	0.2893	0.2542	0.2542	0.2767	0.2950	0.2458
HTC Exergy of Fuel "kW"	21.71	21.87	22.63	25.75	25.75	23.66	22.19	26.63
HTC Exergy of Product "kW"	6.546	6.546	6.546	6.546	6.546	6.546	6.546	6.546

Table-1(c) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454C refrigerants in higher temperature cycle using low GWP HFC+HFO blends (refrigerants) in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T$_{cond}$=50ºC, T_ambient=25ºC, T$_{Eva_HTC}$=-30ºC , T$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,

Cascaded VCRS	System:1	System 2	System 3	System: 4	System 5	System 6	System 7	System: 8
HFC +HFO Blends in HTC	R450A	R513A	R454B	R454C	R448A	R449A	R452A	R452B
HFC +HFO Blends in LTC	R513a	R452b	R513a	R513a	R513A	R513A	R513A	R513A
First Law Cascaded Efficiency COP$_{Cascade}$	0.7425	0.7213	0.7487	0.6709	0.7153	0.6969	0.6293	0.7103
Exergy Destruction Ratio(EDR$_{Cascade}$)	1.680	1.965	1.856	2.187	1.99	2.069	2.398	1.812
Cascaded Exergetic Efficiency	0.3472	0.3373	0.3501	0.3138	0.3345	0.3259	0.2936	0.3556
Exergy of Fuel "kW"	47.36	48.76	46.97	52.41	49.17	50.46	56.01	46.25
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5066	0.5653	0.3035	0.4979	0.4320	0.4575	0.6919	0.3010
LTC Mass flow Rate (Kg/sec)	0.2245	0.1359	0.2245	0.2245	0.2245	0.2245	0.2245	0.2245
W$_{comp_HTC}$ "kW"	34.12	35.25	33.75	39.19	35.94	37.24	42.79	33.03
W$_{comp_LTC}$ "kW"	13.22	13.51	13.22	13.22	13.22	13.22	13.22	13.22
Q$_{Cond_HTC}$ "kW"	82.53	83.92	82.14	87.58	84.33	85.63	91.18	81.42
Q$_{Cond_LTC}$ "kW"	48.39	48.67	48.39	48.39	48.39	48.39	48.39	48.39
Q$_{Eva_HTC}$ "kW"	48.39	48.67	48.39	48.39	48.39	48.39	48.39	48.39
Q$_{Eva_LTC}$ "kW"	35.16	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.660	2.604	2.66	2.660	2.660	2.660	2.660	2.660
First Law HTC Efficiency COP$_{HTC}$	1.417	1.381	1.434	1.235	1.346	1.299	1.131	1.465
HTC Exergy Destruction Ratio(EDR$_{HTC}$)	2.199	2.202	2.083	2.581	2.284	2.402	2.909	2.017
HTC Exergetic Efficiency	0.3206	0.3123	0.3243	0.2793	0.3045	0.2939	0.2558	0.3314
HTC Exergy of Fuel "kW"	34.14	35.25	33.75	39.19	35.94	37.24	42.79	33.03
HTC Exergy of Product "kW"	10.95	11.01	10.95	10.95	10.95	10.95	10.95	10.95

2.2 *Dynamic thermodynamic(energy) and exergetic performances cascaded VCRS using ecofriendly low GWP R450A refrigerant in HTC in higher temperature cycle using ecofriendly low GWP R513a refrigerant in low temperature cycle (System-1)*

It was found that when evaporator temperature is increasing the system first law (energy) performance (COP$_{cascade}$) and exergetic performance is increasing. Similarly, by increasing LTC evaporator temperature from -50ºC to -70ºC, the first law (energy) performance (COP$_{cascade}$) is increasing and exergetic performance is decreasing as shown in table-2(a) respectively. By increasing HTC condenser temperature from 40ºC to 60ºC, the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in Table-2(c) respectively. Similarly by increasing temperature overlapping , the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in table-2(d) to table-2(f) respectively

Table-2(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R450A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, , T_Eva_LTC=-70ºC, Temperature overlapping=10, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

HTC Evaporator temperature (ºC)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency COP_ Cascade	0.7425	0.7602	0.7733	0.7813	0.7838	0.7805	0.7711
Exergy Destruction Ratio(EDR_Cascade)	1.880	1.813	1.765	1.737	1.728	1.740	1.773
Cascaded Exergetic Efficiency	0.3472	0.3555	0.3616	0.3653	0.3665	0.3650	0.3606
Exergy of Fuel "kW"	47.36	46.26	45.48	45.01	44.87	45.06	45.61
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.46	16.45
HTC Mass flow Rate (Kg/sec)	0.5566	0.5068	0.5080	0.5106	0.5145	0.5201	0.5276
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	0.2686	0.283	0.2992
W_comp _HTC"kW"	34.14	31.31	28.67	26.2	23.89	21.71	19.65
W_comp_LTC "kW"	13.22	14.95	16.81	18.81	20.98	23.35	25.96
Q_Cond_HTC "kW"	82.53	81.43	80.65	80.18	80.04	80.23	80.77
Q_Cond_LTC "kW"	48.39	48.39	48.39	48.39	56.14	58.51	61.12
Q_Eva_HTC "kW"	48.39	48.39	48.39	48.39	56.14	48.39	61.12
Q_Eva_LTC "kW"	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.66	2.352	2.092	1.870	1.677	1.506	1.355
First Law HTC Efficiency COP_ HTC	1.417	1.601	1.813	2.060	2.350	2.695	3.111
HTC Exergy Destruction Ratio(EDR_HTC)	2.119	2.10	2.103	2.133	2.20	2.317	2.502
HTC Exergetic Efficiency	0.3206	0.3226	0.3223	0.3191	0.3125	0.3015	0.2847
HTC Exergy of Fuel "kW"	34.14	31.31	28.67	26.2	23.89	21.71	19.65
HTC Exergy of Product "kW"	10.95	10.10	9.329	8.363	7.467	6.546	5.594

Table-2(b) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R450A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_HTC=-30ºC , Temperature overlapping=10, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

LTC Evaporator Temperature (ºC)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency COP_ Cascade	0.7425	0.7962	0.8526	0.9118	0.9739
Exergy Destruction Ratio(EDR_Cascade)	1.880	1.905	1.941	1.991	2.055
Cascaded Exergetic Efficiency	0.3472	0.3443	0.340	0.3344	0.3273
Exergy of Fuel "kW"	47.36	44.17	41.25	38.57	36.11
Exergy of Product "kW"	16.45	15.21	14.02	12.9	11.82
HTC Mass flow Rate (Kg/sec)	0.5066	0.4870	0.4691	0.4526	0.4375
LTC Mass flow Rate (Kg/sec)	0.2245	0.220	0.2556	0.2114	0.2074
W_comp _HTC"kW"	34.14	32.82	31.61	30.50	29.48
W_comp_LTC "kW"	13.22	11.35	9.638	8.068	6.625
Q_Cond_HTC "kW"	82.53	79.33	76.41	73.74	71.28
Q_Cond_LTC "kW"	48.38	46.52	44.80	43.23	41.79
Q_Eva_HTC "kW"	48.38	46.52	44.80	43.23	41.79
Q_Eva_LTC "kW"	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.66	3.098	3.649	4.359	5.308
First Law HTC Efficiency COP_ HTC	1.417	1.417	1.417	1.417	1.417
HTC Exergy Destruction Ratio(EDR_HTC)	2.119	2.119	2.119	2.119	2.119
HTC Exergetic Efficiency	0.3206	0.3206	0.3206	0.3206	0.3206
HTC Exergy of Fuel "kW"	34.14	32.82	31.61	30.50	29.48
HTC Exergy of Product "kW"	10.95	10.52	10.13	9.78	9.453

Table-2(c) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R450A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , T_{Eva_LTC}=-70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%, Compressor efficiency_$_{LTC}$=80%,*

HTC Condenser Temperature (ºC)	60	55	50	45	40
First Law Cascaded Efficiency $COP\_{Cascade}$	0.6121	0.6768	0.7425	0.8019	0.8795
Exergy Destruction Ratio($EDR\_{Cascade}$)	2.493	2.16	1.880	1.640	1.431
Cascaded Exergetic Efficiency	0.2863	0.3165	0.3472	0.3788	0.4113
Exergy of Fuel “kW”	57.45	51.96	47.36	43.42	39.98
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.6035	0.5503	0.5066	0.470	0.4388
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245
W_{comp_HTC}“kW”	44.23	38.74	34.14	30.2	26.76
W_{comp_LTC} “kW”	13.22	13.22	13.22	13.22	13.22
Q_{Cond_HTC} “kW”	92.62	87.13	82.53	78.59	75.15
Q_{Cond_LTC} “kW”	48.39	48.39	48.39	48.39	48.39
Q_{Eva_HTC} “kW”	48.39	48.39	48.39	48.39	48.39
Q_{Eva_LTC} “kW”	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.660	2.660	2.660	2.660	2.660
First Law HTC Efficiency COP_{HTC}	1.094	1.249	1.417	1.602	1.802
HTC Exergy Destruction Ratio(EDR_{HTC})	3.040	2.539	2.119	1.759	1.445
HTC Exergetic Efficiency	0.2475	0.2825	0.3206	0.3625	0.4090
HTC Exergy of Fuel “kW”	44.23	38.74	34.14	30.2	26.76
HTC Exergy of Product “kW”	10.95	10.95	10.95	10.95	10.95

Table-2(d) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R450A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}=50ºC, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , T_{Eva_LTC}=-70ºC, Compressor efficiency_$_{HTC}$=80%, Compressor efficiency_$_{LTC}$=80%,*

Temperature overlapping (ºC)	0	5	10	15
First Law Cascaded Efficiency $COP\_{Cascade}$	0.8379	0.7887	0.7425	0.6989
Exergy Destruction Ratio($EDR\_{Cascade}$)	1.552	1.711	1.880	2.06
Cascaded Exergetic Efficiency	0.3918	0.3688	0.3472	0.3268
Exergy of Fuel “kW”	41.97	44.59	47.36	50.31
Exergy of Product “kW”	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4735	0.4896	0.5066	0.5247
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
W_{comp_HTC}“kW”	31.91	32.99	34.14	35.36
W_{comp_LTC} “kW”	10.06	11.60	13.22	14.95
Q_{Cond_HTC} “kW”	77.14	79.76	82.53	85.48
Q_{Cond_LTC} “kW”	45.23	46.76	48.39	50.12
Q_{Eva_HTC} “kW”	45.23	46.76	48.39	50.12
Q_{Eva_LTC} “kW”	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	3.495	3.032	2.660	2.352
First Law HTC Efficiency COP_{HTC}	1.417	1.417	1.417	1.417
HTC Exergy Destruction Ratio(EDR_{HTC})	2.119	2.119	2.119	2.119
HTC Exergetic Efficiency	0.3206	0.3206	0.3206	0.3206
HTC Exergy of Fuel “kW”	31.91	32.99	34.14	35.36
HTC Exergy of Product “kW”	10.23	11.60	10.95	11.34

2.3 *Dynamic thermodynamic(energy) and exergetic performances cascaded VCRS using ecofriendly low GWP R513a refrigerant in HTC in higher temperature cycle using ecofriendly low GWP R450A refrigerant in low temperature cycle (system-2).*

It was found that when evaporator temperature is increasing the system first law (energy) performance (COP_cascade) and exergetic performance is increasing as shown in table-3(a) respectively. Similarly, by increasing LTC evaporator temperature from -50°C to -70°C, the first law (energy) performance (COP_cascade) is increasing and exergetic performance is decreasing as shown in table-3(b) respectively. By increasing HTC condenser temperature from 40oC to 60oC, the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in table-3(c) respectively. Similarly, by increasing temperature overlapping, the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in table-3(d) to table-3(e) respectively.

Table-2(e) Thermodynamic performances of optimum combinations of cascaded VCRS using ecofriendly low GWP R450A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T\__{Eva\_HTC}$=-30ºC , $T\__{Eva\_LTC}$=-70ºC, Compressor efficiency$__{HTC}$=80%, Compressor efficiency$__{LTC}$=80%,*

Temperature overlapping (ºC)	0	4	8	12
First Law Cascaded Efficiency $COP\__{Cascade}$	0.8379	0.7903	0.7607	0.7248
Exergy Destruction Ratio($EDR\__{Cascade}$)	1.552	1.679	1.811	1.95
Cascaded Exergetic Efficiency	0.3918	0.3733	0.3557	0.3389
Exergy of Fuel “kW”	41.97	44.05	46.23	0.4852
Exergy of Product “kW”	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4735	0.4863	0.4997	0.5137
LTC Mass flow Rate (Kg/sec)	0.2079	0.2142	0.2209	0.2281
$W\__{comp\_HTC}$“kW”	31.91	32.77	33.67	34.62
$W\__{comp\_LTC}$ “kW”	10.06	11.28	12.56	13.90
$Q\__{Cond\_HTC}$ “kW”	77.14	79.22	81.4	83.69
$Q\__{Cond\_LTC}$ “kW”	45.23	46.45	47.73	49.07
$Q\__{Eva\_HTC}$ “kW”	45.23	46.45	47.73	49.07
$Q\__{Eva\_LTC}$ “kW”	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	3.495	3.117	2.80	2.53
First Law HTC Efficiency $COP\__{HTC}$	1.417	1.417	1.417	1.417
HTC Exergy Destruction Ratio($EDR\__{HTC}$)	2.119	2.119	2.119	2.119
HTC Exergetic Efficiency	0.3206	0.3206	0.3206	0.3206
HTC Exergy of Fuel “kW”	31.91	32.77	33.67	34.62
HTC Exergy of Product “kW”	10.23	10.51	10.80	11.10

Table-2(f) Thermodynamic performances of optimum combinations of cascaded VCRS using ecofriendly low GWP R450A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T\__{Eva\_HTC}$=-30ºC , $T\__{Eva\_LTC}$=-70ºC, Compressor efficiency$__{HTC}$=80%, Compressor efficiency$__{LTC}$=80%,*

Temperature overlapping (ºC)	0.0	3	6	9	12	15
First Law Cascaded Efficiency $COP\__{Cascade}$	0.8379	0.8080	0.7792	0.7515	0.7248	0.6989
Exergy Destruction Ratio($EDR\__{Cascade}$)	1.552	1.647	1.744	1.845	1.95	2.06
Cascaded Exergetic Efficiency	0.3918	0.3778	0.3644	0.3514	0.3389	0.3268
Exergy of Fuel “kW”	41.97	43.52	45.13	46.79	0.4852	50.31
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4735	0.4831	0.4929	0.5031	0.5137	0.5247
LTC Mass flow Rate (Kg/sec)	0.2079	0.2126	0.2175	0.2227	0.2281	0.2339
$W\__{comp\_HTC}$“kW”	31.91	32.55	33.22	33.90	34.62	35.36
$W\__{comp\_LTC}$ “kW”	10.06	10.97	11.91	12.89	13.90	14.95
$Q\__{Cond\_HTC}$ “kW”	77.14	78.9	80.3	81.96	83.69	85.48
$Q\__{Cond\_LTC}$ “kW”	45.23	46.14	47.08	48.06	49.07	50.12
$Q\__{Eva\_HTC}$ “kW”	45.23	46.14	47.08	48.06	49.07	50.12
$Q\__{Eva\_LTC}$ “kW”	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	3.495	3.205	2.952	2.728	2.53	2.352
First Law HTC Efficiency $COP\__{HTC}$	1.417	1.417	1.417	1.417	1.417	1.417
HTC Exergy Destruction Ratio($EDR\__{HTC}$)	2.119	2.119	2.119	2.119	2.119	2.119
HTC Exergetic Efficiency	0.3206	0.3206	0.3206	0.3206	0.3206	0.3206
HTC Exergy of Fuel “kW”	31.91	32.55	33.22	33.90	34.62	35.36
HTC Exergy of Product “kW”	10.23	10.44	10.65	10.87	11.10	11.34

2.4 Dynamic thermodynamic (energy) and exergetic performances cascaded VCRS using ecofriendly low GWP R454B refrigerant in HTC in higher temperature cycle using ecofriendly low GWP R513A refrigerant in low temperature cycle(system-3)

It was found that when evaporator temperature is increasing the system first law (energy) performance ($COP\__{cascade}$) and exergetic performance is increasing as shown in Table-4(a) respectively. Similarly, by increasing LTC evaporator temperature from -50ºC to -70ºC, the first law (energy) performance ($COP\__{cascade}$) is increasing and exergetic performance is decreasing as shown in Table-4(b) respectively. By increasing HTC condenser temperature from 40ºC to 60ºC, the first law (energy) performance ($COP\__{cascade}$) and exergetic performance is decreasing as shown in Table-4(c) respectively. Similarly, by increasing temperature overlapping, the first law (energy) performance ($COP\__{cascade}$) and exergetic performance is decreasing as shown in Table-4(d) respectively.

Table-3(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP GWP R513a *refrigerant* in HTC *in higher temperature cycle using low GWP* R452a *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T$_{cond}$=50ºC, T_ambient=25ºC, T$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Evaporator Temperature (ºC)	-30	-25	-20	-15	-10	-5	-5	0
First Law Cascaded Efficiency COP_ Cascade	0.7213	0.7419	0.7587	0.7713	0.7794	0.7827	0.7827	0.7811
Exergy Destruction Ratio(EDR_Cascade)	1.965	1.882	1.818	1.772	1.744	1.732	1.732	1.738
Cascaded Exergetic Efficiency	0.3373	0.3470	0.3548	0.3607	0.3645	0.3660	0.3660	0.3653
Exergy of Fuel “kW”	48.76	47.40	46.35	45.59	45.12	44.93	44.93	45.02
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5653	0.5638	0.5636	0.5646	0.5670	0.5708	0.5708	0.5761
LTC Mass flow Rate (Kg/sec)	0.1359	0.1401	0.1447	0.1496	0.1550	0.1608	0.1608	0.1672
W_comp _HTC“kW”	35.25	32.2	29.36	26.71	24.22	21.87	21.87	19.64
W_comp_LTC “kW”	13.51	15.2	16.99	18.89	20.91	23.07	23.07	25.39
Q_Cond_HTC “kW”	83.92	82.57	81.52	80.76	80.29	80.10	80.10	80.19
Q_Cond_LTC “kW”	48.67	50.37	52.16	54.06	56.07	58.23	58.51	60.55
Q_Eva_HTC “kW”	48.67	50.37	52.16	54.06	56.07	58.23	58.51	48.67
Q_Eva_LTC “kW”	35.16	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.604	2.313	2.070	1.862	1.682	1.525	1.506	1.385
First Law HTC Efficiency COP_ HTC	1.381	1.564	1.777	2.024	2.317	2.663	2.663	3.084
HTC Exergy Destruction Ratio(EDR_HTC)	2.202	2.173	2.167	2.189	2.247	2.356	2.356	2.543
HTC Exergetic Efficiency	0.2348	0.3153	0.3158	0.3136	0.3080	0.2980	0.2980	0.2822
HTC Exergy of Fuel “kW”	35.25	32.2	29.36	26.71	24.22	21.87	21.87	19.64
HTC Exergy of Product “kW”	11.01	10.15	9.272	8.376	7.458	6.515	6.546	5.542

Table-3(b) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R450A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T$_{cond}$=50ºC, T_ambient=25ºC, T$_{Eva_HTC}$=-30ºC , Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

LTC Evaporator Temperature (ºC)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency COP_ Cascade	0.7213	0.7733	0.8277	8846	0.9441
Exergy Destruction Ratio(EDR_Cascade)	1.965	1.991	2.03	2.083	2.151
Cascaded Exergetic Efficiency	0.3373	0.3343	0.3301	0.3244	0.3173
Exergy of Fuel “kW”	48.76	45.48	42.49	39.76	37.25
Exergy of Product “kW”	16.45	15.21	14.02	12.90	11.82
HTC Mass flow Rate (Kg/sec)	0.5653	0.5432	0.5231	0.5047	0.4878
LTC Mass flow Rate (Kg/sec)	0.1359	0.1341	0.1325	0.1309	0.1294
W_comp _HTC“kW”	35.25	33.87	32.62	31.47	30.42
W_comp_LTC “kW”	13.51	11.61	9.872	8.287	6.833
Q_Cond_HTC “kW”	83.92	80.65	77.66	74.92	72.42
Q_Cond_LTC “kW”	48.67	46.77	45.04	43.45	42.0
Q_Eva_HTC “kW”	48.67	46.77	45.04	43.45	42.0
Q_Eva_LTC “kW”	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.604	3.03	3.562	4.244	5.147
First Law HTC Efficiency COP_ HTC	1.381	1.381	1.381	1.381	1.381
HTC Exergy Destruction Ratio(EDR_HTC)	2.202	2.202	2.202	2.202	2.202
HTC Exergetic Efficiency	0.3123	0.3123	0.3123	0.3123	0.3123
HTC Exergy of Fuel “kW”	35.25	33.87	32.62	31.47	30.42
HTC Exergy of Product “kW”	11.01	10.58	10.19	9.829	9.50

Table-3(c) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP GWP R513a *refrigerant* in HTC *in higher temperature cycle using low GWP* R452b *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T_ambient=25ºC, T$_{Eva_HTC}$=-30ºC , T$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Condenser Temperature (ºC)	60	55	50	45	40
First Law Cascaded Efficiency COP_ Cascade	0.5823	0.6515	0.7213	0.7921	0.8643
Exergy Destruction Ratio(EDR_Cascade)	2.672	2.282	1.965	1.70	1.479
Cascaded Exergetic Efficiency	0.2723	0.3047	0.3379	0.3704	0.4040
Exergy of Fuel “kW”	60.39	57.97	48.76	44.39	40.67
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.6918	0.6214	0.5653	0.5194	0.4811
LTC Mass flow Rate (Kg/sec)	0.1359	0.1359	0.1359	0.1359	0.1359
W_comp _HTC“kW”	46.89	40.47	35.25	30.89	27.16

W_comp_LTC "kW"	13.51	13.51	13.51	13.51	13.51
Q_Cond_HTC "kW"	95.56	89.14	83.92	79.56	75.83
Q_Cond_LTC "kW"	48.67	48.67	48.67	48.67	48.67
Q_Eva_HTC "kW"	48.67	48.67	48.67	48.67	48.67
Q_Eva_LTC "kW"	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.604	2.604	2.604	2.604	2.604
First Law HTC Efficiency COP_ HTC	1.038	1.203	1.381	1.576	1.792
HTC Exergy Destruction Ratio(EDR_HTC)	3.258	2.676	2.202	1.805	1.467
HTC Exergetic Efficiency	0.2348	0.2721	0.2348	0.3565	0.4054
HTC Exergy of Fuel "kW"	46.89	40.47	35.25	30.89	27.16
HTC Exergy of Product "kW"	11.01	11.01	11.01	11.01	11.01

Table-3(d) Thermodynamic performances of optimum combinations of cascaded VCRS using ecofriendly low GWP R450A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_HTC=-30ºC , T_Eva_LTC=-70ºC, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

Temperature overlapping (ºC)	0	4	5	8	10	12	15
First Law Cascaded Efficiency COP_ Cascade	0.8115	0.7739	0.7648	0.7384	0.7213	0.7047	0.6805
Exergy Destruction Ratio(EDR_Cascade)	1.635	1.763	1.796	1.896	1.965	2.035	2.142
Cascaded Exergetic Efficiency	0.3795	0.3619	0.3577	0.3453	0.3373	0.3295	0.3182
Exergy of Fuel "kW"	43.22	45.52	45.98	47.63	48.75	49.91	51.68
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5288	0.5429	0.5466	0.5577	0.5653	0.5730	0.5850
LTC Mass flow Rate (Kg/sec)	0.1282	0.1311	0.1319	0.1342	0.1359	0.1375	0.1401
W_comp _HTC"kW"	32.97	33.86	34.08	34.78	35.25	35.73	36.48
W_comp_LTC "kW"	10.36	11.58	10.90	12.85	13.51	14.17	15.20
Q_Cond_HTC "kW"	78.5	80.61	81.15	82.8	83.92	85.07	86.85
Q_Cond_LTC "kW"	45.53	46.75	47.06	48.02	48.67	49.34	50.37
Q_Eva_HTC "kW"	45.53	46.75	47.06	48.02	48.67	49.34	50.37
Q_Eva_LTC "kW"	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	3.394	3.036	2.956	2.736	2.604	2.481	2.313
First Law HTC Efficiency COP_ HTC	1.381	1.381	1.381	1.381	1.381	1.381	1.381
HTC Exergy Destruction Ratio(EDR_HTC)	2.202	2.202	2.202	2.202	2.202	2.202	2.202
HTC Exergetic Efficiency	0.3123	0.3123	0.3123	0.3123	0.3123	0.3123	0.3123
HTC Exergy of Fuel "kW"	32.97	33.86	34.08	34.78	35.25	35.73	36.48
HTC Exergy of Product "kW"	10.3	10.57	10.65	10.86	13.51	11.16	11.39

Table-3(e) Thermodynamic performances of optimum combinations of cascaded VCRS using ecofriendly low GWP R450A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_HTC=-30ºC , T_Eva_LTC=-70ºC, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

Temperature overlapping (ºC)	0	3	6	9	12	15
First Law Cascaded Efficiency COP_ Cascade	0.8115	0.7831	0.7559	0.7298	0.7047	0.6805
Exergy Destruction Ratio(EDR_Cascade)	1.635	1.731	1.829	1.930	2.035	2.142
Cascaded Exergetic Efficiency	0.3795	0.3662	0.3535	0.3413	0.3295	0.3182
Exergy of Fuel "kW"	43.22	44.91	46.52	48.19	49.91	51.68
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5288	0.5393	0.5502	0.5615	0.5730	0.5850
LTC Mass flow Rate (Kg/sec)	0.1282	0.1304	0.1327	0.1350	0.1375	0.1401
W_comp _HTC"kW"	32.97	33.63	34.31	35.01	35.73	36.48
W_comp_LTC "kW"	10.36	11.27	12.21	13.18	14.17	15.20
Q_Cond_HTC "kW"	78.5	80.7	81.69	83.36	85.07	86.85
Q_Cond_LTC "kW"	45.53	46.44	47.38	48.35	49.34	50.37
Q_Eva_HTC "kW"	45.53	46.44	47.38	48.35	49.34	50.37
Q_Eva_LTC "kW"	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	3.394	3.119	2.880	2.669	2.481	2.313
First Law HTC Efficiency COP_ HTC	1.381	1.381	1.381	1.381	1.381	1.381
HTC Exergy Destruction Ratio(EDR_HTC)	2.202	2.202	2.202	2.202	2.202	2.202
HTC Exergetic Efficiency	0.3123	0.3123	0.3123	0.3123	0.3123	0.3123
HTC Exergy of Fuel "kW"	32.97	33.63	34.31	35.01	35.73	36.48
HTC Exergy of Product "kW"	10.3	10.50	10.72	10.94	11.16	11.39

Table-4(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454B refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_$_{LTC}$=35.167 kW, T_$_{cond}$=50ºC, T_ambient=25ºC, T_$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%, Compressor efficiency_$_{LTC}$=80%,*

HTC Evaporator Temperature (ºC)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency COP_ $_{Cascade}$	0.7487	0.7601	0.7677	0.7713	0.7705	0.7649	0.7544
Exergy Destruction Ratio(EDR_$_{Cascade}$)	1.856	1.810	1.785	1.792	1.775	1.796	1.835
Cascaded Exergetic Efficiency	0.3501	0.3554	0.3590	0.3607	0.3603	0.3577	0.3528
Exergy of Fuel "kW"	46.97	46.27	45.81	45.59	45.64	45.97	46.62
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.3035	0.3097	0.3167	0.3246	0.3334	0.3436	0.3552
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	0.2686	0.2830	0.2992
W_$_{comp\ _HTC}$"kW"	33.75	31.31	29.0	26.79	24.67	22.63	20.66
W_$_{comp_LTC}$ "kW"	13.22	14.95	16.81	18.81	20.98	23.35	25.96
Q_$_{Cond_HTC}$ "kW"	82.14	81.44	80.97	80.76	80.81	81.14	81.78
Q_$_{Cond_LTC}$ "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
Q_$_{Eva_HTC}$ "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
Q_$_{Eva_LTC}$ "kW"	35.16	35.16	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.66	2.352	2.092	1.87	1.677	1.506	1.355
First Law HTC Efficiency COP_ $_{HTC}$	1.434	1.601	1.792	2.015	2.276	2.586	2.959
HTC Exergy Destruction Ratio(EDR_$_{HTC}$)	2.083	2.101	2.139	2.203	2.303	2.457	2.693
HTC Exergetic Efficiency	0.3243	0.3225	0.3186	0.3122	0.3027	0.2893	0.2708
HTC Exergy of Fuel "kW"	33.75	31.31	29.0	26.79	24.67	22.63	20.66
HTC Exergy of Product "kW"	10.95	10.10	9.239	8.363	7.467	6.546	5.594

Table-4(b) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454B refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_$_{LTC}$=35.167 kW, T_$_{cond}$=50ºC, T_ambient=25ºC, T_$_{Eva_HTC}$=-30ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%, Compressor efficiency_$_{LTC}$=80%,*

LTC Evaporator Temperature (ºC)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency COP_ $_{Cascade}$	0.7487	0.8030	0.8601	0.9201	0.9831
Exergy Destruction Ratio(EDR_$_{Cascade}$)	1.856	1.88	1.916	1.964	2.027
Cascaded Exergetic Efficiency	0.3501	0.3472	0.3430	0.3374	33.04
Exergy of Fuel "kW"	46.97	43.79	40.89	40.49	35.77
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.3035	0.2918	0.281	0.2712	0.2621
LTC Mass flow Rate (Kg/sec)	0.2345	0.220	0.2156	0.2114	0.2076
W_$_{comp\ _HTC}$"kW"	33.75	32.44	31.25	30.15	29.15
W_$_{comp_LTC}$ "kW"	13.22	11.35	9.638	8.068	6.625
Q_$_{Cond_HTC}$ "kW"	82.14	78.96	76.05	73.39	70.94
Q_$_{Cond_LTC}$ "kW"	48.39	46.52	44.80	43.23	41.79
Q_$_{Eva_HTC}$ "kW"	48.39	46.52	44.80	43.23	41.79
Q_$_{Eva_LTC}$ "kW"	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	3.66	3.098	3.649	4.359	5.308
First Law HTC Efficiency COP_ $_{HTC}$	1.434	1.434	1.434	1.434	1.434
HTC Exergy Destruction Ratio(EDR_$_{HTC}$)	2.083	2.083	2.083	2.083	2.083
HTC Exergetic Efficiency	0.3243	0.3243	0.3243	0.3243	0.3243
HTC Exergy of Fuel "kW"	33.75	32.44	31.25	30.15	29.15
HTC Exergy of Product "kW"	10.95	10.52	10.13	9.78	9.453

Table-4(c) Thermodynamic performances of optimum combinations of cascaded VCRS (System-3) using low GWP R454B refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_$_{LTC}$=35.167 kW, T_$_{cond}$=50ºC, T_ambient=25ºC, T_$_{Eva_HTC}$=-30ºC, T_$_{Eva_LTC}$=-70ºC, , Compressor efficiency_$_{HTC}$=80%, Compressor efficiency_$_{LTC}$=80%,*

HTC Condenser Temperature (ºC)	60	55	50	45	40
First Law Cascaded Efficiency COP_ $_{Cascade}$	0.6185	0.6838	0.7487	0.8145	0.8817
Exergy Destruction Ratio(EDR_$_{Cascade}$)	2.457	2.127	1.856	1.626	1.425
Cascaded Exergetic Efficiency	0.2892	0.3198	0.3501	0.3808	0.4123
Exergy of Fuel "kW"	56.86	51.43	46.97	43.18	39.89
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.3559	0.3267	0.3035	0.2845	0.2685
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245

$W_{\_comp\ \_HTC}$ "kW"	43.63	38.21	33.75	29.96	26.66
$W_{\_comp\_LTC}$ "kW"	13.22	13.22	13.22	13.22	13.22
$Q_{\_Cond\_HTC}$ "kW"	92.02	86.60	82.14	78.39	75.05
$Q_{\_Cond\_LTC}$ "kW"	48.39	48.39	48.39	48.39	48.39
$Q_{\_Eva\_HTC}$ "kW"	48.39	48.39	48.39	48.39	48.39
$Q_{\_Eva\_LTC}$ "kW"	35.16	35.16	35.16	35.16	35.16
First Law LTC Efficiency COP_LTC	2.66	2.66	2.66	2.66	2.66
First Law HTC Efficiency COP_ HTC	1.109	1.267	1.434	1.615	1.815
HTC Exergy Destruction Ratio(EDR_HTC)	2.986	2.127	2.083	1.737	1.425
HTC Exergetic Efficiency	0.2509	0.2865	0.3243	0.3653	0.4123
HTC Exergy of Fuel "kW"	43.63	38.21	33.75	29.96	26.66
HTC Exergy of Product "kW"	10.95	10.95	10.95	10.95	10.95

Table-4(d) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454b *refrigerant* in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50°C, T_ambient=25°C, $T_{\_Eva\_HTC}$=-30°C , $T_{\_Eva\_LTC}$=-70°C, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,*

HTC Condenser Temperature (°C)	0	5	10	15
First Law Cascaded Efficiency COP_ Cascade	0.8452	0.7954	0.7487	0.7046
Exergy Destruction Ratio(EDR_Cascade)	1.53	1.688	1.856	2.035
Cascaded Exergetic Efficiency	0.3952	0.3720	0.3501	0.3295
Exergy of Fuel "kW"	41.61	44.21	46.97	49.91
Exergy of Product "kW"	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.2837	0.2933	0.3035	0.3144
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
$W_{\_comp\ \_HTC}$ "kW"	31.55	32.62	33.75	34.96
$W_{\_comp\_LTC}$ "kW"	10.06	11.60	13.22	14.55
$Q_{\_Cond\_HTC}$ "kW"	76.27	79.38	82.14	85.08
$Q_{\_Cond\_LTC}$ "kW"	45.23	46.76	48.39	50.12
$Q_{\_Eva\_HTC}$ "kW"	45.23	46.76	48.39	50.12
$Q_{\_Eva\_LTC}$ "kW"	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	3.495	3.032	2.66	2.352
First Law HTC Efficiency COP_ HTC	1.434	1.434	1.434	1.434
HTC Exergy Destruction Ratio(EDR_HTC)	2.083	2.083	2.083	2.083
HTC Exergetic Efficiency	0.3243	0.3243	0.3243	0.3243
HTC Exergy of Fuel "kW"	31.55	32.62	33.75	34.96
HTC Exergy of Product "kW"	10.23	10.58	10.95	11.34

2.5 *Dynamic thermodynamic(energy) and exergetic performances cascaded VCRS using ecofriendly low GWP R454C refrigerant in HTC in higher temperature cycle using ecofriendly low GWP R513A refrigerant in low temperature cycle(system-4)*

It was observed that when evaporator temperature is increasing the system first law (energy) performance ($COP_{\_cascade}$) and exergetic performance is increasing as shown in Table-5(a) respectively. Similarly, by increasing LTC evaporator temperature from -50°C to -70°C, the first law (energy) performance ($COP_{\_cascade}$) is increasing and exergetic performance is decreasing as shown in Table-5(b) respectively. By increasing HTC condenser temperature from 40°C to 60°C, the first law (energy) performance ($COP_{\_cascade}$) and exergetic performance is decreasing as shown in Table-5(c) respectively. Similarly by increasing temperature overlapping , the first law (energy) performance ($COP_{\_cascade}$) and exergetic performance is decreasing as shown in Table-5(d) respectively

Table-5(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454C refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50°C, T_ambient=25°C, $T_{\_Eva\_LTC}$=-70°C, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,*

HTC Evaporator Temperature (°C)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency COP_ Cascade	0.6709	0.6885	0.7023	0.7118	0.7166	0.7143	0.7106
Exergy Destruction Ratio(EDR_Cascade)	2.187	2.106	2.045	2.004	1.984	1.985	2.009
Cascaded Exergetic Efficiency	0.3138	0.3220	0.3284	0.3329	0.3351	0.3350	0.3323
Exergy of Fuel "kW"	52.41	51.07	50.07	49.41	49.08	49.10	49.49
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	4979	4995	0.5023	0.5066	0.5125	0.5203	0.4979
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	0.2686	0.2830	0.2992

$W_{\_comp\ \_HTC}$ "kW"	39.19	36.12	33.26	30.60	28.10	2575	23.53
$W_{\_comp\_LTC}$ "kW"	13.22	14.95	16.81	18.81	20.98	23.35	25.96
$Q_{\_Cond\_HTC}$ "kW"	87.58	86.24	85.24	84.57	84.24	84.26	84.65
$Q_{\_Cond\_LTC}$ "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
$Q_{\_Eva\_HTC}$ "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
$Q_{\_Eva\_LTC}$ "kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.660	2.352	2.092	1.87	1.677	1.506	1.355
First Law HTC Efficiency $COP_{\_\ HTC}$	1.235	1.388	1.563	1.764	1.998	2.272	2.598
HTC Exergy Destruction Ratio($EDR_{\_HTC}$)	2.581	2.577	2.60	2.659	2.763	2.934	3.206
HTC Exergetic Efficiency	0.2793	0.2796	0.2778	0.2733	0.2657	0.2542	0.2378
HTC Exergy of Fuel "kW"	39.19	36.12	33.26	30.60	28.10	25.75	23.63
HTC Exergy of Product "kW"	10.95	10.10	9.239	8.363	7.467	6.546	5.594

Table-5(b) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454C refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50°C, T_ambient=25°C, $T_{\_Eva\_HTC}$=-30°C , Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,*

LTC Evaporator Temperature (°C)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency $COP_{\_\ Cascade}$	6709	0.7173	0.7657	8162	0.8689
Exergy Destruction Ratio($EDR_{\_Cascade}$)	2.187	2.224	2.275	2.341	2.424
Cascaded Exergetic Efficiency	0.3136	0.3102	0.3054	0.2993	0.2920
Exergy of Fuel "kW"	52.41	49.03	45.93	43.09	40.47
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4979	0.4787	0.461	0.4448	0.430
LTC Mass flow Rate (Kg/sec)	0.2245	0.220	0.2156	0.2114	0.2074
$W_{\_comp\ \_HTC}$ "kW"	39.19	37.68	36.29	35.02	33.85
$W_{\_comp\_LTC}$ "kW"	13.22	11.35	9.638	8.068	6.625
$Q_{\_Cond\_HTC}$ "kW"	87.58	84.19	81.09	78.25	75.64
$Q_{\_Cond\_LTC}$ "kW"	48.39	43.29	44.80	43.29	41.79
$Q_{\_Eva\_HTC}$ "kW"	48.39	43.29	44.80	43.29	41.79
$Q_{\_Eva\_LTC}$ "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	3.098	3.649	4.359	5.308
First Law HTC Efficiency $COP_{\_\ HTC}$	1.235	1.235	1.235	1.235	1.235
HTC Exergy Destruction Ratio($EDR_{\_HTC}$)	2.581	2.581	2.581	2.581	2.581
HTC Exergetic Efficiency	0.2793	0.2793	0.2793	0.2793	0.2793
HTC Exergy of Fuel "kW"	39.19	37.68	36.29	35.02	33.85
HTC Exergy of Product "kW"	10.95	10.52	10.13	9.78	9.453

Table-5(c) Thermodynamic performances of optimum combinations of cascaded VCRS (System-4) using low GWP R454C refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, T_ambient=25°C, $T_{\_Eva\_HTC}$=-30°C , $T_{\_Eva\_LTC}$=-70°C, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,*

HTC Condenser Temperature (°C)	60	55	50	45	40
First Law Cascaded Efficiency $COP_{\_\ Cascade}$	0.5382	0.6050	0.6709	0.7370	0.8039
Exergy Destruction Ratio($EDR_{\_Cascade}$)	2.973	2.535	2.187	1.901	1.660
Cascaded Exergetic Efficiency	0.2517	0.2829	0.3138	0.3447	0.3759
Exergy of Fuel "kW"	65.34	58.13	52.41	47.72	43.74
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.6136	0.5484	0.4979	0.4575	0.4242
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245
$W_{\_comp\ \_HTC}$ "kW"	52.12	44.91	39.19	34.49	30.52
$W_{\_comp\_LTC}$ "kW"	13.22	13.22	13.22	13.22	13.22
$Q_{\_Cond\_HTC}$ "kW"	100.5	93.30	87.58	82.88	79.91
$Q_{\_Cond\_LTC}$ "kW"	48.39	48.39	48.39	48.39	48.39
$Q_{\_Eva\_HTC}$ "kW"	48.39	48.39	48.39	48.39	48.39
$Q_{\_Eva\_LTC}$ "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.660	2.660	2.660	2.660	2.660
First Law HTC Efficiency $COP_{\_\ HTC}$	0.9285	1.078	1.235	1.403	1.585
HTC Exergy Destruction Ratio($EDR_{\_HTC}$)	3.762	3.103	2.581	2.151	1.788
HTC Exergetic Efficiency	0.210	0.2437	0.2793	0.3173	0.3586
HTC Exergy of Fuel "kW"	52.12	44.91	39.19	34.49	30.52

Table-5(d) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R454C refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_HTC=-30ºC , T_Eva_LTC=-70ºC, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

Temperature overlapping (ºC)	0	5	10	15
First Law Cascaded Efficiency COP_ Cascade	0.7531	0.7108	0.6709	0.6335
Exergy Destruction Ratio(EDR_Cascade)	1.839	2.008	2.187	2.378
Cascaded Exergetic Efficiency	0.3522	0.3324	0.3138	0.2961
Exergy of Fuel “kW”	46.69	49.47	52.41	55.55
Exergy of Product “kW”	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4654	0.4812	0.4979	0.5158
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
W_comp _HTC“kW”	36.63	37.88	39.19	40.59
W_comp_LTC “kW”	10.06	11.60	13.22	14.55
Q_Cond_HTC “kW”	81.86	84.64	87.58	90.72
Q_Cond_LTC “kW”	45.23	46.76	48.39	50.12
Q_Eva_HTC “kW”	45.23	46.76	48.39	50.12
Q_Eva_LTC “kW”	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	3.495	3.032	2.66	2.352
First Law HTC Efficiency COP_ HTC	1.235	1.235	1.235	1.235
HTC Exergy Destruction Ratio(EDR_HTC)	2.581	2.581	2.581	2.581
HTC Exergetic Efficiency	0.2793	0.2793	0.2793	0.2793
HTC Exergy of Fuel “kW”	36.63	37.88	39.19	40.59
HTC Exergy of Product “kW”	10.23	10.58	10.95	11.34

Table-6(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R448A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_LTC=-70ºC, Temperature overlapping=10, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

HTC Evaporator Temperature (ºC)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency COP_ Cascade	0.7153	0.7310	0.7426	0.7495	0.7515	0.7482	0.7394
Exergy Destruction Ratio(EDR_Cascade)	1.99	1.925	1.880	1.853	1.846	1.858	1.892
Cascaded Exergetic Efficiency	0.3345	0.3418	0.3472	0.3505	0.3514	0.3499	0.3458
Exergy of Fuel “kW”	49.17	48.11	47.36	46.92	46.80	47.0	47.56
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4320	0.4351	0.4394	0.4450	0.4521	0.4609	0.4717
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	0.2686	0.2830	0.2992
W_comp _HTC“kW”	35.94	33.15	30.55	28.11	25.82	23.66	21.60
W_comp_LTC “kW”	13.22	14.95	16.81	18.81	20.98	23.35	25.96
Q_Cond_HTC “kW”	84.33	83.27	82.53	82.09	81.96	82.17	82.73
Q_Cond_LTC “kW”	48.39	50.12	51.98	53.91	56.14	58.51	61.12
Q_Eva_HTC “kW”	48.39	50.12	51.98	53.91	56.14	48.39	61.12
Q_Eva_LTC “kW”	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.352	2.092	1.87	1.677	1.506	1.355
First Law HTC Efficiency COP_ HTC	1.346	1.512	1.701	1.92	2.174	2.272	2.660
HTC Exergy Destruction Ratio(EDR_HTC)	2.284	2.283	2.307	2.361	2.458	2.934	2.861
HTC Exergetic Efficiency	0.3045	0.3046	0.3024	0.2975	0.2892	0.2542	0.2590
HTC Exergy of Fuel “kW”	35.14	33.15	30.55	28.11	25.82	25.75	21.60
HTC Exergy of Product “kW”	10.95	10.10	9.239	8.363	7.467	6.546	5.594

2.6 Dynamic thermodynamic and exergetic performances cascaded VCRS using low GWP R448A refrigerant in HTC in higher temperature cycle using low GWP R513A refrigerant in low temperature cycle(system-5)

Thermodynamic performances of cascaded VCRS using ecofriendly low GWP R448A refrigerant in HTC in higher temperature cycle and ecofriendly low GWP R513A refrigerant in low temperature cycle for varying evaporator temperature from 0°C to -30°C and it was found that when evaporator temperature is increasing the system first law (energy) performance (COP_cascade) and exergetic performance is increasing as shown in Table-6(a) respectively. Similarly, by increasing LTC evaporator temperature from -50°C to -70°C, the first law (energy) performance (COP_cascade) is increasing and exergetic performance is decreasing as shown in Table-6(b) respectively. By increasing HTC condenser temperature from 40°C to 60°C, the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in Table-6(c) respectively. Similarly by increasing temperature overlapping , the first law (energy) performance

(COP_cascade) and exergetic performance is decreasing as shown in Table-6(d) respectively.

Table-6(b) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system using ecofriendly low GWP R448A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}=50°C, T_ambient=25°C, T_{Eva_HTC}=-30°C, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

LTC Evaporator Temperature (°C)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency COP_ Cascade	0.7153	0.7661	0.8194	0.8752	0.9336
Exergy Destruction Ratio(EDR_Cascade)	1.99	2.019	2.060	2.116	2.187
Cascaded Exergetic Efficiency	0.3345	0.3313	0.3268	0.3210	0.31.38
Exergy of Fuel "kW"	49.17	45.9	42.92	40.18	37.67
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.432	0.4153	0.40	0.3860	0.3731
LTC Mass flow Rate (Kg/sec)	0.2245	0.22	0.2156	0.2114	0.2074
W_{comp_HTC}"kW"	35.94	34.55	33.28	32.11	31.04
W_{comp_LTC} "kW"	13.22	11.35	9.638	8.068	6.625
Q_{Cond_HTC} "kW"	84.33	81.07	78.09	75.35	72.83
Q_{Cond_LTC} "kW"	48.39	46.52	44.80	43.23	41.79
Q_{Eva_HTC} "kW"	48.39	46.52	44.80	43.23	41.79
Q_{Eva_LTC} "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	3.098	3.649	4.359	5.308
First Law HTC Efficiency COP_ HTC	1.346	1.346	1.346	1.346	1.346
HTC Exergy Destruction Ratio(EDR_HTC)	2.284	2.284	2.284	2.284	2.284
HTC Exergetic Efficiency	0.3045	0.3045	0.3045	0.3045	0.3045
HTC Exergy of Fuel "kW"	35.94	34.55	33.28	32.11	31.04
HTC Exergy of Product "kW"	10.95	10.52	10.13	9.78	9.453

Table-6(c) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system(System-5) using ecofriendly low GWP R448A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_ambient=25°C, T_{Eva_HTC}=-30°C , T_{Eva_LTC}=-70°C, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Condenser Temperature (°C)	60	55	50	45	40
First Law Cascaded Efficiency COP_ Cascade	0.5894	0.6524	0.7153	0.7784	0.8439
Exergy Destruction Ratio(EDR_Cascade)	2.628	2.278	1.99	1.745	1.534
Cascaded Exergetic Efficiency	0.2756	0.3050	0.3345	0.3642	0.3946
Exergy of Fuel "kW"	59.66	53.91	49.17	45.15	41.67
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5136	0.4684	0.4320	0.4019	0.3766
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245
W_{comp_HTC}"kW"	46.44	40.69	35.94	31.93	28.45
W_{comp_LTC} "kW"	13.22	13.22	13.22	13.22	13.22
Q_{Cond_HTC} "kW"	94.83	89.07	84.33	80.32	76.84
Q_{Cond_LTC} "kW"	48.39	48.39	48.39	48.39	48.39
Q_{Eva_HTC} "kW"	48.39	48.39	48.39	48.39	48.39
Q_{Eva_LTC} "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.66	2.66	2.66	2.66
First Law HTC Efficiency COP_ HTC	1.042	1.189	1.346	1.516	1.701
HTC Exergy Destruction Ratio(EDR_HTC)	2.628	2.717	2.284	1.917	1.599
HTC Exergetic Efficiency	0.2357	0.2690	0.3045	0.3428	0.3847
HTC Exergy of Fuel "kW"	46.44	40.69	35.94	31.93	28.45
HTC Exergy of Product "kW"	10.95	10.95	10.95	10.95	10.95

2.7 Dynamic thermodynamic and exergetic performances cascaded using low GWP R449A refrigerant in HTC in higher temperature cycle using low GWP R513A refrigerant in low temperature cycle(system-6)

Table-7(a) and Table-7(b) show the Optimum thermodynamic performances of cascaded vapor compression refrigeration system using ecofriendly low GWP R449A refrigerant in HTC in higher temperature cycle and ecofriendly low GWP R513A refrigerant in low temperature cycle for varying evaporator temperature from 0°C to -30°C and it was found that when evaporator temperature is increasing the system first law (energy) performance (COP_cascade) and exergetic performance is increasing as shown in Table-7(a) respectively.

Similarly, by increasing LTC evaporator temperature from -50°C to -70°C, the first law (energy) performance (COP_cascade) is increasing and exergetic performance is decreasing as shown in Table-7(b) respectively. By increasing HTC condenser temperature from 40°C to 60°C, the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in Table-7(c) respectively. Similarly, by increasing temperature overlapping, the first law (energy) performance (COP_cascade) and exergetic performance is decreasing as shown in Table-7(d) respectively.

Table-6(d) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system using ecofriendly low GWP R448A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T$_{cond}$=50°C, T_ambient=25°C, T$_{Eva_HTC}$=-30°C , T$_{Eva_LTC}$=-70°C, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

Temperature overlapping (°C)	0	5	10	15
First Law Cascaded Efficiency COP$_{Cascade}$	0.8055	0.759	0.7153	0.6739
Exergy Destruction Ratio(EDR$_{Cascade}$)	1.655	1.817	1.990	2.193
Cascaded Exergetic Efficiency	0.3767	0.3549	0.3345	0.3151
Exergy of Fuel “kW”	43.66	46.33	49.39	52.18
Exergy of Product “kW”	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4038	0.4175	0.4320	0.4475
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
W$_{comp_HTC}$“kW”	33.60	34.74	35.94	37.23
W$_{comp_LTC}$ “kW”	10.06	11.60	13.22	14.55
Q$_{Cond_HTC}$ “kW”	78.82	81.5	84.33	87.35
Q$_{Cond_LTC}$ “kW”	45.23	46.76	48.39	50.12
Q$_{Eva_HTC}$ “kW”	45.23	46.76	48.39	50.12
Q$_{Eva_LTC}$ “kW”	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	3.495	3.032	2.66	2.352
First Law HTC Efficiency COP$_{HTC}$	1.346	1.346	1.346	1.346
HTC Exergy Destruction Ratio(EDR$_{HTC}$)	2.284	2.284	2.284	2.284
HTC Exergetic Efficiency	0.3045	0.3045	0.3045	0.3045
HTC Exergy of Fuel “kW”	33.60	34.74	35.94	37.23
HTC Exergy of Product “kW”	10.23	10.58	10.95	11.34

Table-7(a) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system using ecofriendly low GWP R449A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T$_{cond}$=50°C, T_ambient=25°C, T$_{Eva_LTC}$=-70°C, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Evaporator Temperature (°C)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency COP$_{Cascade}$	0.6969	0.7133	0.7259	0.734	0.7375	0.7358	0.7288
Exergy Destruction Ratio(EDR$_{Cascade}$)	2.069	1.998	1.946	1.913	1.90	1.906	1.934
Cascaded Exergetic Efficiency	0.3299	0.3336	0.3394	0.3433	0.3449	0.3441	0.3408
Exergy of Fuel “kW”	50.46	49.30	48.95	47.91	47.69	47.0	48.25
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4575	0.4612	0.4662	0.4724	0.480	0.4894	0.5007
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	2.686	0.2830	0.2992
W$_{comp_HTC}$“kW”	37.34	34.25	31.64	29.10	26.71	24.45	22.29
W$_{comp_LTC}$ “kW”	13.22	14.95	16.81	18.81	20.98	23.35	25.96
Q$_{Cond_HTC}$ “kW”	85.63	84.47	83.62	83.06	82.85	82.96	83.42
Q$_{Cond_LTC}$ “kW”	58.91	50.12	51.98	53.93	56.14	58.51	61.12
Q$_{Eva_HTC}$ “kW”	58.91	50.12	51.98	53.93	56.14	48.39	61.12
Q$_{Eva_LTC}$ “kW”	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.352	2.092	1.87	1.677	1.506	1.355
First Law HTC Efficiency COP$_{HTC}$	1.299	1.459	1.643	1.855	2.102	2.473	2.660
HTC Exergy Destruction Ratio(EDR$_{HTC}$)	2.402	2.401	2.425	2.48	2.577	2.614	2.985
HTC Exergetic Efficiency	0.2939	0.2940	0.2920	0.2874	0.2939	0.2767	0.2590
HTC Exergy of Fuel “kW”	37.34	34.35	31.64	29.10	26.71	23.66	22.29
HTC Exergy of Product “kW”	10.95	10.10	9.239	8.363	7.467	6.546	5.594

Table-7(b) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system using ecofriendly low GWP R449A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}=50ºC, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%, Compressor $efficiency\_{LTC}$=80%,*

LTC Evaporator Temperature (ºC)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency $COP\_{Cascade}$	0.6969	0.7458	0.7971	0.8506	0.9066
Exergy Destruction Ratio($EDR\_{Cascade}$)	2.069	2.101	2.146	2.206	2.282
Cascaded Exergetic Efficiency	0.3299	0.3225	0.3179	0.3119	0.3047
Exergy of Fuel “kW”	50.46	47.15	44.12	41.34	38.79
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4575	0.4398	0.4236	0.4087	0.3951
LTC Mass flow Rate (Kg/sec)	0.2245	0.220	0.2156	0.2114	0.2074
W_{comp_HTC}“kW”	37.34	35.8	34.48	33.27	32.16
W_{comp_LTC} “kW”	13.22	11.35	9.638	8.068	6.625
Q_{Cond_HTC} “kW”	85.63	82.32	79.29	76.51	73.96
Q_{Cond_LTC} “kW”	48.9	46.52	44.80	43.23	41.79
Q_{Eva_HTC} “kW”	48.9	46.52	44.80	43.23	41.79
Q_{Eva_LTC} “kW”	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	3.098	3.649	4.369	5.308
First Law HTC Efficiency COP_{HTC}	1.299	1.299	1.299	1.299	1.299
HTC Exergy Destruction Ratio(EDR_{HTC})	2.402	2.402	2.402	2.402	2.402
HTC Exergetic Efficiency	0.2939	0.2939	0.2939	0.2939	0.2939
HTC Exergy of Fuel “kW”	37.34	35.8	34.48	33.27	32.16
HTC Exergy of Product “kW”	10.95	10.52	10.13	9.78	9.453

Table-7(c) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system(System-6) using ecofriendly low GWP R449A refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , T_{Eva_LTC}=-70ºC, Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%, Compressor $efficiency\_{LTC}$=80%,*

HTC Condenser Temperature (ºC)	60	55	50	45	40
First Law Cascaded Efficiency $COP\_{Cascade}$	0.5635	0.6306	0.6969	0.7634	0.8309
Exergy Destruction Ratio($EDR\_{Cascade}$)	2.795	2.391	2.069	1.801	1.573
Cascaded Exergetic Efficiency	0.2635	0.2949	0.3259	0.3570	0.3886
Exergy of Fuel “kW”	62.41	55.77	50.46	46.07	42.32
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.5566	0.5009	0.4575	0.4224	0.3933
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245
W_{comp_HTC}“kW”	49.19	42.55	37.24	32.84	29.10
W_{comp_LTC} “kW”	13.22	13.22	13.22	13.22	13.22
Q_{Cond_HTC} “kW”	97.58	90.94	85.63	81.23	77.49
Q_{Cond_LTC} “kW”	48.39	48.39	48.39	48.39	48.39
Q_{Eva_HTC} “kW”	48.39	48.39	48.39	48.39	48.39
Q_{Eva_LTC} “kW”	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.66	2.66	2.66	2.66
First Law HTC Efficiency COP_{HTC}	0.9838	1.137	1.299	1.437	1.663
HTC Exergy Destruction Ratio(EDR_{HTC})	3.494	2.887	2.402	2.001	1.658
HTC Exergetic Efficiency	0.2225	0.2573	0.2939	0.3333	0.3762
HTC Exergy of Fuel “kW”	49.19	42.55	37.24	32.84	29.10
HTC Exergy of Product “kW”	10.95	10.95	10.95	10.95	10.95

2.8 Dynamic thermodynamic and exergetic performances cascaded VCRS using low GWP R452A refrigerant in HTC in higher temperature cycle using low GWP R513A refrigerant in low temperature cycle(system-7)

It was observed that when evaporator temperature is increasing the system first law (energy) performance (COP_cascade) and exergetic performance is increasing as shown in Table-8(a) respectively. Similarly, by increasing LTC evaporator temperature from -50°C to -70°C, the first law (energy) performance (COP_cascade) is increasing and exergetic performance is decreasing as shown in Table-8(b) respectively. By increasing HTC condenser temperature from 40°C to 60°C, the first law performance and exergetic performance is decreasing as shown in Table-8(c) respectively. Similarly, by increasing temperature overlapping, the first law (energy) performance and exergetic performance is decreasing as shown in Table-8(d) respectively.

Table-7(d) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R449A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_HTC=-30ºC , T_Eva_LTC=-70ºC, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

HTC Condenser Temperature (ºC)	0	5	10	15
First Law Cascaded Efficiency COP_ Cascade	0.7837	0.7390	0.6969	0.6570
Exergy Destruction Ratio(EDR_Cascade)	1.729	1.894	2.069	2.255
Cascaded Exergetic Efficiency	0.3665	0.3456	0.3259	0.3072
Exergy of Fuel "kW"	44.87	47.59	50.46	53.53
Exergy of Product "kW"	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.4276	0.4421	0.4575	0.4738
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
W_comp _HTC"kW"	34.81	35.99	37.24	38.57
W_comp_LTC "kW"	10.06	11.60	13.22	14.55
Q_Cond_HTC "kW"	80.04	82.75	85.63	88.7
Q_Cond_LTC "kW"	45.23	46.76	48.39	50.12
Q_Eva_HTC "kW"	45.23	46.76	48.39	50.12
Q_Eva_LTC "kW"	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	3.495	3.032	2.66	2.352
First Law HTC Efficiency COP_ HTC	1.299	1.299	1.299	1.299
HTC Exergy Destruction Ratio(EDR_HTC)	2.402	2.402	2.402	2.402
HTC Exergetic Efficiency	0.2939	0.2939	0.2939	0.2939
HTC Exergy of Fuel "kW"	34.81	35.99	37.24	38.57
HTC Exergy of Product "kW"	10.23	10.58	10.95	11.34

Table-8(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R452A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_LTC=-70ºC, Temperature overlapping=10, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

HTC Evaporator Temperature (ºC)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency COP_ Cascade	0.6279	0.6519	0.6720	0.6878	0.6985	0.7723	0.7606
Exergy Destruction Ratio(EDR_Cascade)	2.406	2.28	2.182	2.109	2.026	1.762	1.812
Cascaded Exergetic Efficiency	0.2936	0.3048	0.3143	0.3216	0.3266	0.3612	0.3557
Exergy of Fuel "kW"	56.10	53.95	52.33	51.13	50.35	45.54	46.24
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.6919	0.6884	0.6873	0.6885	0.6924	0.3395	0.3510
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	0.2686	0.2830	0.2992
W_comp _HTC"kW"	42.79	38.99	35.52	32.33	29.37	22.19	20.28
W_comp_LTC "kW"	13.22	14.95	16.81	18.81	20.98	23.35	25.96
Q_Cond_HTC "kW"	91.18	89.11	87.50	86.30	85.52	80.7	81.40
Q_Cond_LTC "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
Q_Eva_HTC "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
Q_Eva_LTC "kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.352	2.092	1.87	1.677	1.506	1.355
First Law HTC Efficiency COP_ HTC	1.131	1.285	1.463	1.67	1.911	2.637	3.014
HTC Exergy Destruction Ratio(EDR_HTC)	2.909	2.28	2.844	2.865	2.933	2.390	2.625
HTC Exergetic Efficiency	0.2558	0.2590	0.2601	0.2587	0.2542	0.2950	0.2759
HTC Exergy of Fuel "kW"	42.79	38.99	35.52	32.33	29.37	22.19	20.28
HTC Exergy of Product "kW"	13.22	10.10	9.239	8.363	7.467	6.546	5.594

Table-8(b) Thermodynamic performances of optimum combinations of cascaded VCRS system using low GWP R452A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_LTC=35.167 kW, T_cond=50ºC, T_ambient=25ºC, T_Eva_HTC=-30ºC, Temperature overlapping=10, Compressor efficiency_HTC=80%, Compressor efficiency_LTC=80%,*

LTC Evaporator Temperature (ºC)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency COP_ Cascade	0.6279	0.6701	0.7140	0. 7596	0.8070
Exergy Destruction Ratio(EDR_Cascade)	2.406	2.451	2.512	2.59	2.687
Cascaded Exergetic Efficiency	0.2936	0.2897	0.2840	0.2786	0.2712
Exergy of Fuel "kW"	56.01	52.48	49.24	46.30	0.4358
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.6919	0.6651	0.6406	0.6182	0.5976
LTC Mass flow Rate (Kg/sec)	0.2245	0.220	0.2156	0.2114	0.2074

$W\_{comp\ \_HTC}$"kW"	42.79	41.13	39.62	38.23	36.95
W_{comp_LTC} "kW"	13.22	11.35	9.638	8.068	6.625
Q_{Cond_HTC} "kW"	91.18	87.65	84.42	81.46	78.75
Q_{Cond_LTC} "kW"	48.39	46.52	44.80	43.23	41.79
Q_{Eva_HTC} "kW"	48.39	46.52	44.80	43.23	41.79
Q_{Eva_LTC} "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	3.098	3.649	4.359	5.308
First Law HTC Efficiency $COP\_{\ HTC}$	1.131	1.131	1.131	1.131	1.131
HTC Exergy Destruction Ratio(EDR_{HTC})	2.909	2.909	2.909	2.909	2.909
HTC Exergetic Efficiency	0.2558	0.2558	0.2558	0.2558	0.2558
HTC Exergy of Fuel "kW"	42.79	41.13	39.62	38.23	42.79
HTC Exergy of Product "kW"	10.95	10.52	10.13	9.78	9.453

Table-8(c) Thermodynamic performances of optimum combinations of cascaded VCRS (System-7) using low GWP R452A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T_ambient=25°C, T_{Eva_HTC}=-30°C , T_{Eva_LTC}=-70°C, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Condenser Temperature (°C)	60	55	50	45	40
First Law Cascaded Efficiency $COP\_{\ Cascade}$	0.4660	0.5487	0.6279	0.7055	0.7830
Exergy Destruction Ratio($EDR\_{Cascade}$)	3.509	2.878	2.406	2.031	1.731
Cascaded Exergetic Efficiency	0.2179	0.2566	0.2936	0.3299	0.3662
Exergy of Fuel "kW"	75.47	64.10	56.01	49.84	44.91
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.9311	0.790	0.6919	0.6189	0.5620
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245
$W\_{comp\ \_HTC}$"kW"	62.25	50.87	42.79	36.62	31.69
W_{comp_LTC} "kW"	13.22	13.22	13.22	13.22	13.22
Q_{Cond_HTC} "kW"	110.6	99.26	91.18	85.01	80.08
Q_{Cond_LTC} "kW"	48.39	48.39	48.39	48.39	48.39
Q_{Eva_HTC} "kW"	48.39	48.39	48.39	48.39	48.39
Q_{Eva_LTC} "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.66	2.66	2.66	2.66
First Law HTC Efficiency $COP\_{\ HTC}$	0.7774	0.9512	1.131	1.321	1.527
HTC Exergy Destruction Ratio(EDR_{HTC})	4.687	3.648	2.909	2.346	1.895
HTC Exergetic Efficiency	0.1758	0.2152	0.2558	0.2989	0.3454
HTC Exergy of Fuel "kW"	62.25	50.87	42.79	36.62	31.69
HTC Exergy of Product "kW"	10.95	10.95	10.95	10.95	10.95

Table-8(d) Thermodynamic performances of optimum combinations of cascaded VCRS system using low GWP R452A refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle (Q_Eva$_{LTC}$=35.167 kW, T_{cond}=50°C, T_ambient=25°C, T_{Eva_HTC}=-30°C , T_{Eva_LTC}=-70°C, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Condenser Temperature (°C)	0	5	10	15
First Law Cascaded Efficiency $COP\_{\ Cascade}$	0.7026	0.6642	0.6279	0.5933
Exergy Destruction Ratio($EDR\_{Cascade}$)	2.044	2.220	2.406	2.604
Cascaded Exergetic Efficiency	0.3285	0.3106	0.2936	0.2775
Exergy of Fuel "kW"	50.05	52.95	56.01	0.5927
Exergy of Product "kW"	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.6467	0.6687	0.6919	0.7167
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
$W\_{comp\ \_HTC}$"kW"	39.99	41.35	42.79	44.32
W_{comp_LTC} "kW"	10.06	11.60	13.22	14.55
Q_{Cond_HTC} "kW"	85.22	88.11	91.98	94.44
Q_{Cond_LTC} "kW"	45.23	46.76	48.39	50.12
Q_{Eva_HTC} "kW"	45.23	46.76	48.39	50.12
Q_{Eva_LTC} "kW"	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	3.495	3.032	2.66	2.352
First Law HTC Efficiency $COP\_{\ HTC}$	1.131	1.131	1.131	1.131
HTC Exergy Destruction Ratio(EDR_{HTC})	2.909	2.909	2.909	2.909
HTC Exergetic Efficiency	0.2558	0.2558	0.2558	0.2558
HTC Exergy of Fuel "kW"	39.99	41.35	42.79	44.32

2.9 Dynamic thermodynamic and exergetic performances cascaded VCRS using low GWP R452B refrigerant in HTC in higher temperature cycle using low GWP R513A refrigerant in low temperature cycle(system-7)

Thermodynamic performances of cascaded vapor compression refrigeration system using ecofriendly low GWP R452B refrigerant in HTC in higher temperature cycle and ecofriendly low GWP R513A refrigerant in low temperature cycle for varying evaporator temperature from 0ºC to -30ºC and it was found that when evaporator temperature is increasing the system first law (energy) performance ($COP_{\_cascade}$) and exergetic performance is increasing as shown in Table-9(a) respectively. Similarly, by increasing LTC evaporator temperature from -50ºC to -70ºC, the first law (energy) performance ($COP_{\_cascade}$) is increasing and exergetic performance is decreasing as shown in Table-9(b) respectively. By increasing HTC condenser temperature from 40ºC to 60ºC, the first law (energy) performance ($COP_{\_cascade}$) and exergetic performance is decreasing as shown in Table-9(c) respectively. Similarly by increasing temperature overlapping ,the first law (energy) performance ($COP_{\_cascade}$) and exergetic performance is decreasing as shown in Table-9(d) respectively

Table-9(a) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R452BA refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,*

HTC Evaporator Temperature (ºC)	-30	-25	-20	-15	-10	-5	0
First Law Cascaded Efficiency $COP_{\_Cascade}$	0.7603	0.7712	0.7782	0.7809	0.7790	0.7037	0.7031
Exergy Destruction Ratio($EDR_{\_Cascade}$)	1.812	1.773	1.748	1.739	2.237	2.039	2.042
Cascaded Exergetic Efficiency	0.3596	0.3607	0.3639	0.3652	0.3643	0.3291	0.3288
Exergy of Fuel "kW"	46.25	45.60	45.19	45.04	45.14	49.97	50.02
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.3010	0.3068	0.3133	0.3209	0.3295	0.6990	0.7087
LTC Mass flow Rate (Kg/sec)	0.2245	0.2339	0.2443	0.2558	0.2686	0.2830	0.2992
$W_{\_comp\ \_HTC}$"kW"	33.03	30.64	28.38	26.23	24.17	26.63	24.06
$W_{\_comp\_LTC}$ "kW"	20.98	18.81	16.81	14.95	13.22	23.35	25.96
$Q_{\_Cond\_HTC}$ "kW"	81.42	80.77	80.36	80.20	80.13	85.14	85.19
$Q_{\_Cond\_LTC}$ "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
$Q_{\_Eva\_HTC}$ "kW"	48.39	50.12	51.98	53.97	56.14	58.51	61.12
$Q_{\_Eva\_LTC}$ "kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.352	2.092	1.87	1.677	1.506	1.355
First Law HTC Efficiency $COP_{\_HTC}$	1.465	1.636	1.831	2.058	2.323	2.197	2.54
HTC Exergy Destruction Ratio($EDR_{\_HTC}$)	2.017	2.034	2.072	2.136	2.237	3.068	3.301
HTC Exergetic Efficiency	0.3314	0.3296	0.3255	0.3652	0.3090	0.2458	0.2325
HTC Exergy of Fuel "kW"	33.03	30.64	28.38	26.23	24.17	26.63	24.06
HTC Exergy of Product "kW"	13.22	10.10	9.239	8.363	7.467	6.546	5.594

Table-9(b) Thermodynamic performances of optimum combinations of cascaded VCRS using low GWP R452B refrigerant in HTC *in higher temperature cycle using low GWP* R513a *refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC , Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_LTC}$=80%,*

LTC Evaporator Temperature (ºC)	-70	-65	-60	-55	-50
First Law Cascaded Efficiency $COP_{\_Cascade}$	1.0	0.9358	0.8744	0.8159	0.7603
Exergy Destruction Ratio($EDR_{\_Cascade}$)	1.812	1.835	1.868	1.914	1.914
Cascaded Exergetic Efficiency	0.3556	0.3528	0.3487	0.3432	0.3363
Exergy of Fuel "kW"	46.25	43.10	40.22	37.58	35.15
Exergy of Product "kW"	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.3010	0.2894	0.2787	0.2689	0.260
LTC Mass flow Rate (Kg/sec)	0.2245	0.220	0.2156	0.2114	0.2074
$W_{\_comp\ \_HTC}$"kW"	33.03	31.75	30.58	29.51	28.53
$W_{\_comp\_LTC}$ "kW"	13.22	11.35	9.638	8.068	6.625
$Q_{\_Cond\_HTC}$ "kW"	81.42	78.27	75.39	78.27	81.42
$Q_{\_Cond\_LTC}$ "kW"	48.39	46.52	44.80	43.23	41.79
$Q_{\_Eva\_HTC}$ "kW"	48.39	46.52	44.80	43.23	41.79
$Q_{\_Eva\_LTC}$ "kW"	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	3.098	3.649	4.359	5.308
First Law HTC Efficiency $COP_{\_HTC}$	1.465	1.465	1.465	1.465	1.465
HTC Exergy Destruction Ratio($EDR_{\_HTC}$)	2.017	2.017	2.017	2.017	2.017
HTC Exergetic Efficiency	0.3314	0.3314	0.3314	0.3314	0.3314
HTC Exergy of Fuel "kW"	33.03	31.75	30.58	29.51	28.53

Table-9(c) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system using ecofriendly low GWP R452B refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a(*System-8*) *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , T_{Eva_LTC}=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Condenser Temperature (ºC)	60	55	50	45	40
First Law Cascaded Efficiency $COP\_{Cascade}$	0.6307	0.6956	0.7603	0.8262	0.8939
Exergy Destruction Ratio($EDR\_{Cascade}$)	2.39	2.074	1.812	1.588	1.392
Cascaded Exergetic Efficiency	0.2950	0.3253	0.3556	0.3863	0.4180
Exergy of Fuel “kW”	55.75	50.56	46.25	42.57	39.34
Exergy of Product “kW”	16.45	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.3502	0.3229	0.3010	0.2828	0.2673
LTC Mass flow Rate (Kg/sec)	0.2245	0.2245	0.2245	0.2245	0.2245
W_{comp_HTC}“kW”	42.53	37.34	33.03	29.34	26.12
W_{comp_LTC} “kW”	13.22	13.22	13.22	13.22	13.22
Q_{Cond_HTC} “kW”	90.92	85.73	81.42	77.73	74.51
Q_{Cond_LTC} “kW”	48.39	48.39	48.39	48.39	48.39
Q_{Eva_HTC} “kW”	48.39	48.39	48.39	48.39	48.39
Q_{Eva_LTC} “kW”	35.167	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	2.66	2.66	2.66	2.66	2.66
First Law HTC Efficiency COP_{HTC}	1.138	1.296	1.465	1.649	1.853
HTC Exergy Destruction Ratio(EDR_{HTC})	2.886	2.411	2.017	1.681	1.386
HTC Exergetic Efficiency	0.2574	0.2932	0.3314	0.3730	0.4191
HTC Exergy of Fuel “kW”	42.53	37.34	33.03	29.34	26.12
HTC Exergy of Product “kW”	10.95	10.95	10.95	10.95	10.95

Table-9(d) Thermodynamic performances of optimum combinations of cascaded vapor compression refrigeration system using ecofriendly low GWP R452b refrigerant in HTC *in higher temperature cycle using ecofriendly low GWP* R513a *refrigerant in low temperature cycle (Q_Eva_{LTC}=35.167 kW, T_{cond}=50ºC, T_ambient=25ºC, T_{Eva_HTC}=-30ºC , T_{Eva_LTC}=-70ºC, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{LTC}$=80%,*

HTC Condenser Temperature (ºC)	0	5	10	15
First Law Cascaded Efficiency $COP\_{Cascade}$	0.8591	0.8080	0.7603	0.7153
Exergy Destruction Ratio($EDR\_{Cascade}$)	1.489	1.646	1.812	1.99
Cascaded Exergetic Efficiency	0.4018	0.3779	0.3556	0.3345
Exergy of Fuel “kW”	40.93	43.52	46.25	49.16
Exergy of Product “kW”	16.45	16.45	16.45	16.45
HTC Mass flow Rate (Kg/sec)	0.2813	0.2909	0.3010	0.3118
LTC Mass flow Rate (Kg/sec)	0.2079	0.2158	0.2245	0.2339
W_{comp_HTC}“kW”	30.87	31.922	33.03	34.21
W_{comp_LTC} “kW”	10.06	11.60	13.22	14.55
Q_{Cond_HTC} “kW”	76.10	78.68	81.42	84.33
Q_{Cond_LTC} “kW”	45.23	46.76	48.39	50.12
Q_{Eva_HTC} “kW”	45.23	46.76	48.39	50.12
Q_{Eva_LTC} “kW”	35.167	35.167	35.167	35.167
First Law LTC Efficiency COP_LTC	3.495	3.032	2.66	2.352
First Law HTC Efficiency COP_{HTC}	1.465	1.465	1.465	1.465
HTC Exergy Destruction Ratio(EDR_{HTC})	2.017	2.017	2.017	2.017
HTC Exergetic Efficiency	0.3314	0.3314	0.3314	0.3314
HTC Exergy of Fuel “kW”	30.87	31.922	33.03	34.21

3. Conclusions

Following conclusions were made using HFC+HFO blends for Replacing R404a, R410a and R12, R22, R502, R507a

- Static thermodynamic performances of cascaded vapor compression refrigeration systems using eight different combinations of HFC +HFO Blends in high temperature cycle at -30ºC in HTC evaporator and two different HFC +HFO Blends (R513a and R R452a) in low temperature cycle and it was found that optimal cascaded vapor compression refrigeration system-2 using R454B in high temperature cycle and R513A in low temperature cycle gives highest first law efficiency and exergetic efficiency with lower power consumption in the both compressors along with lowest system exergy destruction ratioThe lowest thermodynamic performances was observed by using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R454B low GWP refrigerant in low temperature cycle in the Cascaded thermodynamic performances of vapor compression refrigeration

- Cascaded vapor compression refrigeration system using R454B in high temperature cycle and R513A in low temperature cycle at -90ºC gives higher first law efficiency and exergetic efficiency and lower exergy destruction ratio
- Dynamic Thermodynamic performances of cascaded vapor compression refrigeration system using ecofriendly low GWP R450A refrigerant in HTC in higher temperature cycle using ecofriendly low GWP R513a refrigerant in low temperature cycle and R513a refrigerant in low temperature cycle for varying evaporator temperature from 0ºC to -30ºC and it was found that when evaporator temperature is increasing the system first law (energy) performance ($COP\_{cascade}$) and exergetic performance is increasing.
- By increasing LTC evaporator temperature from -50ºC to -70ºC in the all eight cascaded optimal vapor compression refrigeration systems, the first law (energy) performance ($COP\_{cascade}$) is increasing and exergetic performance is decreasing
- By increasing HTC condenser temperature from 40ºC to 60ºC, in the all eight cascaded optimal vapor compression refrigeration systems, the first law (energy) performance ($COP\_{cascade}$) and exergetic performance is decreasing.
- By increasing temperature overlapping, in the all eight cascaded optimal vapor compression refrigeration systems, the first law (energy) performance ($COP\_{cascade}$) and exergetic performance is decreasing respectively

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