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Optimization of two-stage cascade refrigeration systems using HFO refrigerants in the high-temperature circuit and HFC-134a in low-temperature circuit

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Abstract

The eco-friendly refrigeration technologies which are receiving more and more attention in the days by day of for solving energy and environmental problems. In this paper, it is suggested to phase out presently most used refrigerant R-134a considering global warming and to use natural refrigerants such as ammonia, carbon dioxide and hydro carbons in two stage cascade vapour compression refrigeration system for sustainable environment. Thermal model was developed for single stage and also two stage cascade refrigeration systems using HFO-1234yf for low temperature applications in the range of 100$^{\circ C}$ to -51.5$^{\circ C}$ and HFO-1234ze for high temperature applications in the range of 100$^{\circ C}$ to -30.5$^{\circ C}$. Numerical computation was carried out by using R1234ze in the temperature range of 60$^{\circ C}$to -30$^{\circ C}$in the high temperature circuit and R1234yf in the range of 20$^{\circ C}$to -50$^{\circ C}$for low temperature range. The developed model can also predicts the thermal performances of using nine eco-friendly refrigerants in low temperature circuit and R1234ze n low temperature applications. The ecofriendly refrigerants HFO can replace R134a without minor modifications. However up to temperature -50$^{\circ C}$in the low temperature evaporator circuit with temperature overlapping (Approach=10^{o}C) and condenser temperature of 55$^{\circ C}$with cascade evaporator temperature of 0$^{\circ C}$, the combination of R1234ze in high temperature circuit and R1234yf in low temperature circuit gives best results for replacing R134a and for -100$^{\circ C}$of low temperature evaporator circuit and 55$^{\circ C}$of high temperature condenser and -30$^{\circ C}$ cascade evaporator with temperature overlapping (Approach=10^{o}C) the combination of R1234ze – and R245fa gives better thermodynamic performances as compared to R-1234yf and R245fa. The optimum values for system-6 (using R1234ze in high temperature circuit and HFC-134a in low temperature circuit , the optimum second law efficiency (exergetic efficiency) obtained at low temperature evaporator is at -78$^{\circ C}$to -80$^{\circ C}$respectively and no optimum was found using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit.

1. Introduction

Refrigerant selection based on a simple approach of ‘zero ODP’ required high cost to both global warming and energy efficiency. The alarming increase in atmospheric concentration of HFC-134a suggested careful considerations of not overusing any single compound for substituting ODSs. The use of refrigeration will continue to expand worldwide, especially in developing countries, because it is vital to life. However, the environmental impacts, both on the ozone layer and on global warming are important. The refrigeration sector has already helped to mitigate global warming by applying the Montreal Protocol, for improved refrigeration technologies. The chemical industry is promoting new refrigerant it calls ‘hydro fluoro-olefins’(i.e. HFOs). Chemically, HFOs are HFCs. The refrigeration industry has been working for the past few decades to find replacement refrigerants for the ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) being phased out as a result of the Montreal Protocol. The solution for most refrigerant producers has been the commercialization of hydrofluorocarbon (HFC) refrigerants. The new HFC refrigerants, HFC-134a being the most widely used at this time, have zero ozone depletion potential and thus are not affected by the current regulatory phase out as a result of the Montreal Protocol[1].Further environmental regulations may ultimately cause global phase out of certain HFC refrigerants. Currently, the refrigeration industry is facing regulations relating to global warming potential for refrigerants used in mobile air-conditioning. Therefore, there is a great current need to identify new refrigerants with reduced global warming potential for the mobile air-conditioning market. Should the regulations be more broadly applied in the future, for instance for stationary air conditioning and refrigeration systems, an even greater need will be felt for refrigerants that can be used in all areas of the refrigeration and air-conditioning industry. Currently, proposed replacement refrigerants for HFC-134a include HFC-152a, pure hydrocarbons such as butane or propane, or "natural" refrigerants such as CO2. Many of these suggested replacements are toxic, flammable, and/or have low energy efficiency. New replacements are also being proposed for R1234yf and R1234ze among others. As these replacements are found, new uses of such alternative refrigerants are being sought in order to take advantage of their low or zero ozone depletion potential and lower global warming potential because GWP is a measure of a greenhouse gas when it is released into the atmosphere and benchmarked against CO2 which has a GWP equal to one so-called ‘natural’ or ‘stable’ gases such as carbon dioxide, methane and butane, do not break down in the atmosphere and are non-flammable

2.Ecofriendly low GWO & zero ODP hydro-fluoro-olefin (HFO-1234yf)

DuPont and Honeywell [2] jointly identified HFO-1234yf ($CF_3CF{=}CH_2$) as a single substance as the preferred low GWP refrigerant which offers thermal performance.HFO-1234yf is the leading alternative refrigerant to replace R-134a has excellent environmental properties, very low GWP of four, zero ODP, for favourable life cycle climate performance (LCCP) (Spatz et.al, 2008)[3], Atmospheric chemistry determined low toxicity similar to R-134a due to system performances are very similar to R-134a. Excellent COP and Capacity, no glide temperature.The only problem is HFOs are mildly flammable .HFO-1234yf has recently been approved as a class–A2L refrigerant by American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). Despite carbon dioxide’s appeal as a ‘‘natural refrigerant’’ and favourable findings in some reported bench and vehicle tests, as a single compound refrigerant, HFO-1234yf offers similar thermos-physical properties to R-134a, thus minimizing equipment changes and has met criteria for stability and compatibility. The Society of Automotive Engineers (SAE) validated that HFO-1234yf as safe for use in automotive applications. The critical temperature, critical density and critical pressure were measured by the visual observation

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of the meniscus disappearance and were determined to be 367.85 K, 478 kg/m3, and 3382 kPa, respectively (Tanaka and Higashi 2010)[4]. After independent review of all toxicology test results, DuPont and Honeywell have concluded that HFO1234yf is safe to commercialize for use in refrigeration and air conditioning systems.Furthermore, industry risk assessments of various potential exposure scenarios have also concluded HFO-1234yf is safe for use in MAC applications. HFO-1234yf flammability characteristics are much more favourable than those of hydrocarbon gases. It is far less dangerousthanotherhydro-carbonrefrigerants.HFO-1234yf offers equivalent or lower toxicity as compared to R-134a or R-12 in terms of both human health effects and ecological effects. HFO-1234yf met all key technical customer criteria to be adopted for MAC. Various LCCP evaluations done showing LCCP benefit of HFO-1234yf compared to HFC-134a and CO2 (Spatzet al. 2008) [3].HFO-1234yf is not yet a proven entity and even though it may not be commercialized for at least a year or two, it is nevertheless promoted by the chemical industry as the alternative to HFC-134a, The currently available, safe, environmentally friendly, efficient and low GWP, non-fluorocarbon alternatives such as CO2 in refrigeration and air conditioning systems or the commercialization of hydrocarbon (SAE International 2008) (Table 1) because CO2 manufacturers also argue that, CO2 is proven, safe, natural and sustainable for environmental point of view (Spatz Mark 2009)[3] as compared to HFO-1234yf. The Greenpeace Germany had raised flammability , stating that ‘‘the HFO-1234yf will be an alternative for replacing R134a. The Thermodynamic properties of several fluorinated propene isomers, namely: R-1225ye (E), R-1225ye (Z), R-1225zc, R-1234ye (E), R-1234yf, R-1234ze (E), R-1234ze (Z), and R-1243zf for the naming convention for the fluorinated propene series) (Steven Brown et al. 2010)[5].Hydro-Fluro-Olefin (HFO)-1234yf in direct expansion systems (‘‘secondary loop’’) systems employing an intermediate heat transfer fluid. According to DuPont and Honeywell’s R1234yf is a near drop in replacement to HFC-134a . because R744 on the other hand, operates at higher pressure so requires a new re system design with new components and tooling. So selection of proper refrigerant is very important. One can select the refrigerant as per the application, the environmental and physiological properties and performance parameters. Tetra fluoropropene (HFO-1234ze) is a hydro-fluoro-olefin. It was developed as a "fourth generation" refrigerant to replace R-134a and as a blowing agent for foam and aerosol applications.[2] The use of R-134a is being phased out because of its high global-warming potential. HFO-1234ze has zero ozone-depletion potential (ODP=0) and a very low global-warming potential (GWP <1), even lower than CO2

3.Cascade two stages vapour compression refrigeration systems using ecofriendly refrigerants

A cascade refrigeration system having at least two refrigeration loops, each circulating a refrigerant therethrough, comprising (a) first refrigeration loop, including:

(a) a first expansion device for reducing the pressure and temperature of a first refrigerant liquid

(b) an evaporator having an inlet and an outlet, wherein the first refrigerant liquid from the first expansion device enters the evaporator through the evaporator inlet and is evaporated in the evaporator to form a first refrigerant vapor, thereby producing cooling, and circulates to the outlet;

(c) a first compressor having an inlet and an outlet, wherein the first refrigerant vapor from the evaporator circulates to the inlet of the first compressor and is compressed, thereby increasing the pressure and the temperature of the first refrigerant vapor, and the compressed first refrigerant vapor circulates to the outlet of the first compressor; a cascade heat exchanger system comprising: (i) a first cascade heat exchanger having: (A) a first inlet and a first outlet, wherein the first refrigerant vapor from the evaporator circulates from the first inlet to the first outlet and is condensed in the first heat exchanger to form a first refrigerant liquid, thereby rejecting heat, and (B) a second inlet and a second outlet, wherein a heat transfer fluid circulates from the second inlet to the second outlet, wherein the heat rejected by the first refrigerant vapour as it is condensed is absorbed by the heat transfer fluid, (ii) a second cascade heat exchanger having: (A) a first inlet and a first outlet, wherein the heat transfer fluid from the first cascade heat exchanger circulates from the first inlet to the first outlet and rejects the heat absorbed in the first cascade heat exchanger, and (B) a second inlet and a second outlet, wherein a second refrigerant liquid circulates from the second inlet to the second outlet and absorbs the heat rejected by the heat transfer fluid and forms a second refrigerant vapor; a second compressor having an inlet and an outlet, wherein the second refrigerant vapor from the second cascade heat exchanger is drawn into the compressor and is compressed, thereby increasing the pressure and temperature of the second refrigerant vapor; a condenser having an inlet and an outlet for circulating the second refrigerant vapor therethrough and for condensing the second refrigerant vapor from the compressor to form a second refrigerant liquid, wherein the second refrigerant liquid exits the condenser through the outlet; and (g) a second expansion device for reducing the pressure and temperature of the second refrigerant liquid exiting the condenser and entering the second inlet of the second cascade heat exchanger.A method of exchanging heat between at least two refrigeration loops, comprising: (a) absorbing heat from a body to be cooled in a first refrigeration loop and rejecting this heat to a second refrigeration loop; and (b) absorbing the heat from the first refrigeration loop in the second refrigeration loop and rejecting this heat to ambient, wherein the refrigerant in at least one of the refrigeration loops comprises a fluoro-olefin.

4. Results and Discussion

The input data for computing thermal performance of single stage and two tages cascade refrigeration system is given as.

4.1 For two stages cascade refrigeration System-1, System-2, System-3

High temperature condenser temperature (T_Cond_HTC) =50˚C, High temperature evaporator temperature (T_Eva_HTC)=0˚C, Low temperature Evaporator temperature (T_Eva_LTC)=-50˚C, Approach (Temperature overlapping)=10˚C,
Efficiency of Compressor_HTC=0.80,
Efficiency of Compressor_LTC=0.80

4.2 For twostages cascade refrigeration system-4

High temperature condenser temperature (T_Cond_HTC) =55˚C, High temperature Evaporator temperature (T_Eva_HTC) =0˚C, Low temperature evaporator temperature(T_Eva_LTC)= - 50˚C, Approach (Temperature overlapping)=10˚C,
Efficiency of Compressor_HTC=0.80,
Efficiency of Compressor_LTC=0.80

4.3 For cascade refrigeration System-5 & system-6

High temperature condenser temperature (T_Cond_HTC) =55˚C, High temperature Evaporator temperature(T_Eva_HTC) =-30˚C, Low temperature Evaporator temperature(T_Eva_LTC)=-100˚C, Approach (Temperature overlapping)=10oC,
Efficiency of Compressor_HTC=0.80,
Efficiency of Compressor_LTC=0.80

4.4 For vapour compression refrigerationsystem-7

High temperature condenser temperature (T_Cond_)=55˚C,
Evaporator temperature (T_Eva)_= -30˚C,
Efficiency of Compressor=0.80,
The two stages cascade system of consisting of the first refrigerant comprises HFO- 1234yf wherein the second refrigerant comprises HFO-1234ze.Table-1 shows the properties of HFO-1234yf and R-134a

Table 1(a): Physical properties comparison of R1234yf and R134a [3]

Properties	HFO-1234 yf	R-134a
Boiling Point (˚C)	-29	-26
Critical Point ((˚C)	95	102
Vapour Press (25 (˚C) MPa	0.677	0.665
Liquid Density (kg/m3) (25 (˚C)	1,094	1,207
Vapour Density (kg/m3)(25 (˚C)	37.6	32.4

As pure substance R1234ze is seen as the R134a replacement for high temperature application. However, its volumetric refrigerating capacity is below that of R134a and R1234yf. Its boiling point is also higher than that of R134a Similarly to R134a, R1234ze is a medium pressure refrigerant with a slightly higher critical and boiling temperatures and lower critical pressure. Some of the properties of R1234ze in comparison to R134a are listed in the Table 1(b).

Table 1 (b) : Physical properties comparison of R1234ze and R134a [6]

Physical properties	R1234ze	R134a
Molecular weight, kg/mol	114	102
Boiling point at 101.3 kPa, °C	-18,95	-26,06
Critical temperature, °C	109,4	101,1
Critical pressure, bar	36,4	40,6
Latent heat of vaporization at 30 °C, kJ/kg	162,9	173,1
Critical density, kg/m3	489	515,3

The performance of vapour compression system using following eco-friendly refrigerants have been computed and results of thermal model are shown in Table-1, 2, 3, 4, 5, 6 for system 1,2,3,4, 5 and 6 respectively. Thermal performance of System-3 with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit.

Table-2(a): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 “kW”

Effect of Temperature Overlapping (Approach)	COP	System EDR	Exergetic Efficiency	EDR$_{\_Rational}$	Exergy of Fuel (kW)	Exergy of Product kW)	COP_HTC	COP_LTC
0	1.402	1.121	0.4715	0.5285	25.08	11.83	3.737	2.844
2	1.356	1.193	0.4561	0.5439	25.93	11.83	3.737	2.698
4	1.312	1.267	0.4412	0.5588	26.81	11.83	3.737	2.562
6	1.269	1.344	0.4267	0.5733	27.72	11.83	3.737	2.435
8	1.227	1.423	0.4127	0.5873	28.66	11.83	3.737	2.316
10	1.187	1.506	0.3991	0.6009	29.64	11.83	3.737	2.204
12	1.147	1.592	0.3858	0.6142	30.66	11.83	3.737	2.098

Table-2(b): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 “kW”

Effect of Temperature Overlapping (Approach)	COP	W$_{Comp\_HTC}$	W$_{Comp\_LTC}$	Mass flow rate in HTC circuit (kg/sec)	Mass flow rate in LTC circuit (kg/sec)	Q$_{\_Cond\_HTC}$ (kW)	Q$_{\_Cond\_Cascade}$(kW)	Q_Eva$_{\_LTC}$(kW)
0	1.402	12.72	12.37	0.3924	0.2695	60.25	47.53	35.167
2	1.356	12.9	13.04	0.3979	0.2749	61.1	48.2	35.167
4	1.312	13.08	13.73	0.4036	0.2805	61.98	48.89	35.167
6	1.269	13.27	14.44	0.4096	0.2864	62.89	49.61	35.167
8	1.227	13.47	15.19	0.4157	0.2927	63.83	50.35	35.167
10	1.187	13.68	15.96	0.4221	0.2992	64.81	51.13	35.167
12	1.147	13.89	16.76	0.4287	0.3061	65.82	51.93	35.167

Table-2(c): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 “kW”

LTC Refrigerants	COP	System EDR	Exergetic Efficiency	EDR$_{\_Rational}$	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP_LTC
R-134a	1.219	1.438	0.4101	0.5899	28.84	11.83	3.737	2.294
R-1234yf	1.181	1.506	0.3991	0.6009	29.64	11.83	3.737	2.204
R717	1.206	1.466	0.4055	0.5945	29.17	11.83	3.737	2.256
R141b	1.289	1.307	0.4334	0.5666	27.29	11.83	3.737	2.493
R-404a	1.151	1.584	0.3870	0.6130	30.57	11.83	3.737	2.107
R-410a	1.214	1.45	0.4081	0.5919	28.98	11.83	3.737	2.278
R-407c	1.094	1.717	0.3680	0.6320	32.14	11.83	3.737	1.961
R-152a	1.246	1.386	0.4192	0.5808	28.22	11.83	3.737	2.370
R-227ea	1.131	1.629	0.3804	0.6196	31.09	11.83	3.737	2.056
R-236fa	1.188	1.503	0.3995	0.6005	29.6	11.83	3.737	2.207
R-245fa	1.239	1.40	0.4166	0.5834	28.39	11.83	3.737	2.349
R-32	1.203	1.471	0.4047	0.5953	29.22	11.83	3.737	2.250
R-600a	1.215	1.447	0.4087	0.5923	28.94	11.83	3.737	2.282
R-600	1.243	1.392	0.4180	0.5820	28.3	11.83	3.737	2.360
R-290	1.218	1.442	0.4096	0.5904	28.88	11.83	3.737	2.290
R-123	1.259	1.361	0.4235	0.5735	27.93	11.83	3.737	2.408
R-125	1.13	1.632	0.380	0.620	31.13	11.83	3.737	2.052
R-507a	1.168	1.546	0.3928	0.6072	30.11	11.83	3.737	2.153

Table-2(d): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

LTC Refrigerants	COP	W_{Comp_HTC} (kW)	W_{Comp_LTC} (kW)	Mass flow rate in HTC circuit (kg/sec)	Mass flow rate in LTC circuit (kg/sec)	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$ (kW)	Q_Eva$_{\_LTC}$ (kW)
R-134a	1.219	13.51	15.33	0.4169	0.2282	64.01	50.5	35.167
R-1234yf	1.181	13.68	15.96	0.4221	0.2992	64.81	51.13	35.167
R717	1.206	13.58	15.59	0.4194	0.03072	64.34	50.75	35.167
R141b	1.289	13.18	14.10	0.4068	0.1819	62.45	49.27	35.167
R-404a	1.151	13.88	16.69	0.4281	0.2867	65.73	51.86	35.167
R-410a	1.214	13.54	15.44	0.4128	0.188	64.15	50.81	35.167
R-407c	1.094	14.21	17.93	0.4384	0.2109	67.31	53.10	35.167
R-152a	1.246	13.38	14.84	0.4128	0.1390	63.38	50.0	35.167
R-227ea	1.131	13.99	17.10	0.4315	0.433	66.26	52.27	35.167
R-236fa	1.188	13.67	15.93	0.4218	0.3118	64.77	51.10	35.167
R-245fa	1.239	13.42	14.91	0.4139	0.2556	63.55	50.14	35.167
R-32	1.203	13.59	15.63	0.4194	0.1258	64.39	50.80	35.167
R-600a	1.215	13.53	15.41	0.4175	0.1342	64.11	50.57	35.167
R-600	1.243	13.40	14.9	0.4133	0.1206	63.46	50.07	35.167
R-290	1.218	13.52	15.36	0.4171	0.121	64.04	50.53	35.167

Table-2(e): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

HTC Refrigerants	COP	System EDR	Exergetic Efficiency	EDR$_{\_Rational}$	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP_LTC
R1234ze	1.187	1.506	0.3991	0.6009	29.64	11.83	3.737	2.204
R717	1.228	1.422	0.4129	0.5871	28.64	11.83	4.030	2.204
R152a	1.217	1.442	0.4095	0.5905	28.89	11.83	3.955	2.204
R290	1.178	1.523	0.3963	0.6037	29.84	11.83	3.682	2.204
R600	1.217	1.442	0.4095	0.5905	28.89	11.83	3.955	2.204
R600a	1.196	1.486	0.4022	0.5978	29.41	11.83	3.801	2.204
R134a	1.190	1.498	0.4003	0.5997	29.55	11.83	3.762	2.204
R1234yf	1.160	1.564	0.390	0.610	30.32	11.83	3.559	2.204

Table-2(f): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

HTC Refrigerants	COP	W_{Comp_HTC} (kW)	W_{Comp_LTC} (kW)	Mass flow rate in HTC circuit (kg/sec)	Mass flow rate in LTC circuit (kg/sec)	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$ (kW)	Q$_{\_EVA\_LTC}$ (kW)
R1234ze	1.187	13.89	16.76	0.4287	0.3061	65.82	51.93	35.167
R717	1.228	12.89	16.76	0.04964	0.3061	64.81	51.93	35.167
R152a	1.217	13.13	16.76	0.2305	0.3061	65.06	51.93	35.167
R290	1.178	14.10	16.76	0.2058	0.3061	66.03	51.93	35.167
R600	1.217	13.13	16.76	0.1887	0.3061	65.06	51.93	35.167
R600a	1.196	13.66	16.76	0.2187	0.3061	65.59	51.93	35.167
R134a	1.190	13.8	16.76	0.3856	0.3061	65.73	51.93	35.167
R1234yf	1.160	14.59	16.76	0.5086	0.3061	66.52	51.93	35.167

Table-2(g): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

T_Cond (^{o}C)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_ HTC	COP_LTC
60	1.024	1.905	0.3443	0.6557	34.35	11.83	2.779	2.204
55	1.104	1.694	0.3712	0.6288	31.86	11.83	3.215	2.204
50	1.187	1.506	0.3991	0.6009	29.64	11.83	3.737	2.204
45	1.273	1.336	0.4280	0.5720	27.63	11.83	4.379	2.204
40	1.363	1.182	0.4583	0.5417	25.81	11.83	5.192	2.204
35	1.458	1.039	0.4903	0.5097	24.12	11.83	6.264	2.204

30	1.559	0.9070	0.5244	0.4756	22.56	11.83	7.75	2.204
25	1.667	0.7832	0.5608	0.4392	21.09	11.83	9.962	2.204

Table-2(h): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= 0ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Cond (ºC)	COP	W_c$_{\_HTC}$ (kW)	W_c$_{\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R-1234yf	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$ (kW)	Q_EVA $_{\_LTC}$ (kW)
60	1.024	18.68	16.76	0.4892	0.3061	70.61	51.93	35.167
55	1.104	16.15	16.76	0.4587	0.3061	68.08	51.93	35.167
50	1.187	13.89	16.76	0.4287	0.3061	65.82	51.93	35.167
45	1.273	11.86	16.76	0.4042	0.3061	63.79	51.93	35.167
40	1.363	10.0	16.76	0.3827	0.3061	61.93	51.93	35.167
35	1.458	8.29	16.76	0.3636	0.3061	60.22	51.93	35.167
30	1.559	6.701	16.76	0.3464	0.3061	58.63	51.93	35.167
25	1.667	5.212	16.76	0.3310	0.3061	57.14	51.93	35.167

Table-2(i): Variation of Thermal performance with variation of cascade evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= 0ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Eva (ºC)	COP	EDR	Exergetic Efficiency	EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP_LTC
20	1.049	1.836	0.3527	0.6473	33.54	11.83	8.032	1.356
15	1.099	1.706	0.3696	0.6304	32.0	11.83	6.415	1.533
10	1.139	1.611	0.383	0.6170	30.88	11.83	5.264	1.729
5	1.168	1.546	0.3928	0.6072	30.11	11.83	4.404	1.951
4	1.173	1.536	0.3944	0.6056	29.99	11.83	4.257	1.998
3	1.177	1.527	0.3958	0.6042	29.89	11.83	4.118	2.048
2	1.180	1.519	0.3970	0.6030	29.79	11.83	3.985	2.098
1	1.184	1.512	0.3981	0.6019	29.71	11.83	3.858	2.15
0	1.187	1.506	0.3991	0.6009	29.64	11.83	3.737	2.204
-1	1.189	1.501	0.3999	0.6001	29.58	11.83	3.622	2.259
-2	1.191	1.497	0.4005	0.5995	29.53	11.83	3.511	2.316
-3	1.193	1.493	0.4011	0.5989	29.49	11.83	3.405	2.374
-4	1.193	1.491	0.4015	0.5985	29.46	11.83	3.304	2.435
-5	1.194	1.489	0.4017	0.5983	29.44	11.83	3.206	2.497
-6	1.195	1.489	0.4018	0.5991	29.43	11.83	3.113	2.562
-7	1.195	1.489	0.4018	0.5982	29.44	11.83	3.023	2.629
-8	1.194	1.490	0.4016	0.5984	29.45	11.83	2.937	2.698
-9	1.193	1.492	0.4014	0.5986	29.47	11.83	2.854	2.77
-10	1.192	1.494	0.4009	0.5991	29.5	11.83	2.744	2.844
-15	1.180	1.519	0.3969	0.6031	29.8	11.83	2.416	3.261
-20	1.159	1.585	0.3899	0.6101	30.33	11.83	2.116	3.777

Table-2(j): Variation of Thermal performance with variation of cascade evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-1234yf in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= 0ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Eva (ºC)	COP	W$_{\_Comp\_HTC}$ (kW)	W$_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R-1234yf	Q$_{\_Cond}$ $_{\_HTC}$ (kW)	Q$_{\_Cond}$ $_{\_Cascade}$ (kW)	Q$_{\_EVA\_LTC}$ (kW)
20	1.049	7.772	27.26	0.4638	0.4018	70.19	62.42	35.167
15	1.099	9.237	24.09	0.4513	0.3719	68.49	59.26	35.167
10	1.139	10.73	21.34	0.4416	0.3467	67.24	56.51	35.167
5	1.168	12.28	18.92	0.4342	0.3349	66.37	54.09	35.167
4	1.173	12.60	18.47	0.4329	0.3210	66.24	53.64	35.167
3	1.177	12.92	18.03	0.4318	0.3171	66.11	53.20	35.167
2	1.180	13.24	17.60	4307	0.3133	66.01	52.76	35.167
1	1.184	13.57	17.17	0.4297	0.3096	65.91	52.34	35.167
0	1.187	13.89	16.76	0.4287	0.3061	65.82	51.93	35.167
-1	1.189	14.23	16.36	0.4278	0.3026	65.75	51.52	35.167
-2	1.191	14.56	15.96	0.4270	0.2992	65.69	51.13	35.167
-3	1.193	14.91	15.57	0.4262	0.2959	65.64	50.74	35.167
-4	1.193	15.24	15.19	0.4255	0.2927	65.60	50.35	35.167
-5	1.194	15.59	14.81	0.4248	0.2895	65.57	49.98	35.167
-6	1.195	15.94	14.44	0.4242	0.2864	65.55	49.61	35.167
-7	1.195	16.29	14.08	0.4237	0.2834	65.54	49.25	35.167
-8	1.194	16.65	13.73	0.4232	0.2805	65.54	48.89	35.167

-9	1.193	17.01	13.38	0.4227	0.2777	65.55	48.55	35.167
-10	1.192	17.37	13.04	0.4223	0.2749	65.58	48.20	35.167
-15	1.180	19.27	11.40	0.4210	0.2618	65.84	46.57	35.167
-20	1.159	21.29	9.887	0.4207	0.2901	66.35	45.05	35.167

Table-3(a): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= -10ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Cond (ºC)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\_LTC}$
25	1.724	0.7246	0.5798	0.4202	20.4	11.83	9.962	2.294
30	1.61	0.8470	0.5414	0.4586	21.84	11.83	7.75	2.294
35	1.503	0.9777	0.5056	0.4944	23.39	11.83	6.264	2.294
40	1.404	1.118	0.4721	0.5279	25.05	11.83	5.192	2.294
45	1.309	1.271	0.4403	0.5597	26.86	11.83	4.379	2.294
50	1.219	1.438	0.4101	0.5899	28.84	11.83	3.737	2.294
55	1.133	1.624	0.3811	0.6189	31.03	11.83	3.215	2.294
60	1.05	1.832	0.3531	0.6469	33.50	11.83	2.779	2.294

Table-3(b): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= 0ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Cond (ºC)	COP	W$_{\_Comp\_HTC}$ (kW)	W$_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R-1234yf	Q_Cond$_{\_HTC}$ (kW)	Q_Cond$_{\_Cascade}$ (kW)	Q$_{\_EVA\_LTC}$ (kW)
25	1.724	5.069	15.33	0.3219	0.2282	55.56	50.5	35.167
30	1.61	6.516	15.33	0.3369	0.2282	57.01	50.5	35.167
35	1.503	8.062	15.33	0.3535	0.2282	58.56	50.5	35.167
40	1.404	9.726	15.33	0.3721	0.2282	60.22	50.5	35.167
45	1.309	11.53	15.33	0.3931	0.2282	62.03	50.5	35.167
50	1.219	13.51	15.33	0.4169	0.2282	64.01	50.5	35.167
55	1.133	15.71	15.33	0.4441	0.2282	66.20	50.5	35.167
60	1.05	18.17	15.33	0.4758	0.2282	68.66	50.5	35.167

Table-3(c): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= -10ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Eva (ºC)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\_LTC}$
-50	1.219	1.438	0.4101	0.5899	28.84	11.83	3.737	2.294
-45	1.331	1.446	0.4088	0.5912	26.41	10.8	3.737	2.622
-40	1.454	1.465	0.4057	0.5943	24.18	9.811	3.737	3.017
-35	1.589	1.497	0.4005	0.5995	24.14	8.866	3.737	3.503
-30	1.737	1.544	0.3931	0.6069	20.25	7.96	3.737	4.112
-25	1.90	1.611	0.383	0.6170	18.51	7.09	3.737	4.899
-20	2.081	1.702	0.3701	0.6699	16.9	6.255	3.737	5.951

Table-3(d): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= 0ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Eva (ºC)	COP	W$_{\_Comp\_HTC}$ (kW)	W$_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{HTC}$ _(kW)	Q_Cond $_{\_Cascade}$ (kW)	Q_EVA$_{\_LTC}$ (kW)
-50	1.219	13.51	15.33	0.4169	0.2282	64.01	50.5	35.167
-45	1.331	13.0	13.41	0.4031	0.2236	61.58	48.54	35.167
-40	1.454	12.53	11.66	0.3885	0.2192	59.36	46.82	35.167
-35	1.589	12.1	10.04	0.3732	0.2149	57.3	45.21	35.167
-30	1.737	11.7	8.552	0.3609	0.2109	55.42	43.72	35.167
-25	1.90	11.33	7.179	0.3449	0.2070	53.68	42.35	35.167
-20	2.081	10.99	5.91	0.3391	0.2033	52.07	41.08	35.167

Table-3(e): Variation of Thermal performance with variation of cascade evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50ºC with subcooling of 5ºC, T_$_{Eva\_HTC}$= 0ºC, T_$_{Eva\_LTC}$=-50ºC, Q_$_{Eva\_LTC}$=35 "kW"

T_Eva (^{o}C)	COP	$W_{\_Comp\_HTC}$ (kW)	$W_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R-1234yf	$Q_{\_Cond\_HTC}$ (kW)	$Q_{\_Cond\_Cascade}$ (kW)	$Q_{\_EVA\_LTC}$ (kW)
20	1.134	7.327	23.64	0.4372	0.2793	66.17	58.85	35.167
15	1.169	8.801	21.29	0.430	0.2642	65.26	56.56	35.167
10	1.194	10.31	19.13	0.4243	0.2508	64.61	54.30	35.167
5	1.211	11.88	17.15	0.420	0.2389	64.2	52.32	35.167
4	1.214	12.2	16.78	0.4193	0.2367	64.14	51.94	35.167
3	1.216	12.52	16.41	0.4186	0.2345	64.10	51.57	35.167
2	1.217	12.85	16.04	0.4180	0.2324	64.06	51.21	35.167
1	1.218	13.18	15.68	0.4174	0.2303	64.03	50.85	35.167
0	1.219	13.51	15.33	0.4169	0.2282	64.01	50.5	35.167
-1	1.22	13.85	14.98	0.4164	0.2262	64.0	50.15	35.167
-2	1.22	14.19	14.64	0.4159	0.2242	63.99	49.8	35.167
-3	1.22	14.53	14.30	0.4155	0.2223	63.99	49.47	35.167
-4	1.219	14.87	13.97	0.4152	0.2204	64.01	49.13	35.167
-5	1.219	15.22	13.64	0.4148	0.2185	64.03	48.8	35.167
-6	1.217	15.57	13.31	0.4145	0.2167	64.05	48.48	35.167
-7	1.216	15.93	12.99	0.4143	0.2149	64.09	48.16	35.167
-8	1.214	16.29	12.68	0.4141	0.2132	64.14	47.84	35.167
-9	1.212	16.65	12.37	0.4139	0.2114	64.19	47.53	35.167
-10	1.209	17.02	12.06	0.4137	0.2097	64.25	47.23	35.167
-15	1.192	18.93	10.58	0.4135	0.2017	64.67	45.74	35.167
-20	1.167	20.96	9.176	0.4141	0.1943	65.30	44.34	35.167

Table-3(f): Variation of Thermal performance with variation of cascade evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 “kW”

T_Eva (^{o}C)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_ HTC	COP$_{\_LTC}$
20	1.134	1.621	0.3815	0.6185	31.01	11.83	8.032	1.485
15	1.169	1.544	0.3930	0.6070	30.09	11.83	6.415	1.652
10	1.194	1.489	0.4017	0.5983	29.44	11.83	5.264	1.838
5	1.211	1.455	0.4074	0.5936	29.03	11.83	4.408	2.05
4	1.214	1.45	0.4082	0.5918	28.98	11.83	4.257	2.096
3	1.216	1.446	0.4088	0.5912	28.93	11.83	4.118	2.144
2	1.217	1.443	0.4094	0.5906	28.89	11.83	3.985	2.192
1	1.218	1.44	0.4098	0.5902	28.86	11.83	3.858	2.242
0	1.219	1.438	0.4101	0.5899	28.84	11.83	3.737	2.294
-1	1.22	1.437	0.4103	0.5897	28.83	11.83	3.622	2.347
-2	1.22	1.437	0.4103	0.5897	28.82	11.83	3.511	2.402
-3	1.22	1.437	0.4103	0.5897	28.83	11.83	3.405	2.459
-4	1.219	1.438	0.4101	0.5899	28.84	11.83	3.304	2.518
-5	1.219	1.440	0.4098	0.5902	28.86	11.83	3.206	2.579
-6	1.217	1.442	0.4094	0.5906	28.89	11.83	3.113	2.641
-7	1.216	1.445	0.4089	0.5911	28.92	11.83	3.023	2.706
-8	1.214	1.449	0.4083	0.5917	28.97	11.83	2.937	2.774
-9	1.212	1.454	0.4075	0.5925	29.02	11.83	2.854	2.844
-10	1.209	1.459	0.4067	0.5933	29.08	11.83	2.774	2.916
-15	1.192	1.495	0.4009	0.5991	29.51	11.83	2.416	3.325
-20	1.167	1.548	0.3925	0.6075	30.13	11.83	2.116	3.832

Table-3(g): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 “kW”

Effect of Temperature Overlapping (Approach)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\_LTC}$
0	1.424	1.088	0.4789	0.5211	24.7	11.83	3.737	2,916
2	1.36	1.154	0.4642	0.5358	25.48	11.83	3.737	2.774
4	1.338	1.222	0.450	0.550	26.29	11.83	3.737	2.641
6	1.297	1.295	0.4362	0.5638	27.11	11.83	3.737	2.518
8	1.258	1.364	0.4229	0.5771	27.96	11.83	3.737	2.402
10	1.219	1.438	0.4101	0.5899	28.84	11.83	3.737	2.294

12	1.182	1.515	0.3977	0.6023	29.74	11.83	3.737	2.192

Table-3(h): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

Effect of Temperature Overlapping (Approach)	COP	W_{Comp_HTC}	W_{Comp_LTC}	Mass flow rate in HTC circuit (kg/sec)	Mass flow rate in LTC circuit (kg/sec)	Q$_{\_Cond\ \_HTC}$ (kW)	Q$_{\_Cond\ \_Cascade}$(kW)	Q$_{\_Cond\ \_LTC}$(kW)
0	1.424	12.64	12.06	0.3899	0.2097	59.86	47.23	35.167
2	1.36	12.8	12.68	0.3950	0.2132	60.85	47.84	35.167
4	1.338	12.97	13.31	0.4002	0.2167	61.45	48.48	35.167
6	1.297	13.15	13.97	0.4056	0.2204	62.28	49.13	35.167
8	1.258	13.33	14.64	0.4112	0.2242	63.13	49.80	35.167
10	1.219	13.51	15.33	0.4169	0.2282	64.01	50.50	35.167
12	1.182	13.7	16.04	0.4228	0.2324	64.91	51.21	35.167

Table-4(a): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapourcompression refrigeration system using HFO-1234yf in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

Effect of Temperature Overlapping (Approach)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\_LTC}$
0	1.388	1.141	0.4670	0.5330	25.33	11.83	3.559	2.916
2	1.346	1.204	0.4528	0.5472	26.12	11.83	3.559	2.774
4	1.306	1.227	0.4391	0.5609	26.94	11.83	3.559	2.641
6	1.266	1.348	0.4259	0.5741	27.77	11.83	3.559	2.518
8	1.228	1.421	0.4131	0.5869	28.63	11.83	3.559	2.402
10	1.191	1.496	0.4007	0.5993	29.52	11.83	3.559	2.294
12	1.156	1.573	0.3887	0.6113	30.43	11.83	3.559	2.192

Table-4(b): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFO-134a in low temperature circuit forT_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= 0^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

Effect Temperature Overlapping (Approach)	COP	W$_{\_Comp\_HTC}$ (kW)	W$_{\_Comp\_\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R1234yf	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$ (kW)	Q$_{\_EVA\ \_LTC}$ (kW)
0	1.388	13.27	12.06	0.4626	0.2097	60.50	47.23	35.167
2	1.346	13.44	12.66	0.4686	0.2132	61.29	47.84	35.167
4	1.306	13.62	13.31	0.4748	0.2167	62.10	48.48	35.167
6	1.266	13.81	13.97	0.4813	0.2204	62.94	49.13	35.167
8	1.228	13.99	14.64	0.4878	0.2242	63.80	49.8	35.167
10	1.191	14.19	15.33	0.4948	0.2282	64.68	50.5	35.167
12	1.156	14.39	16.04	0.5016	0.2304	65.60	51.27	35.167

Table-4(c): Variation of Thermal performance with variation of cascade evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50^{o}C with subcooling of 5^{o}C, T$_{\_Eva\_HTC}$= -10^{o}C, T$_{\_Eva\_LTC}$=-50^{o}C, Q$_{\_Eva\_LTC}$=35 "kW"

T_Eva (ºC)	COP	EDR	Exergetic Efficiency	EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP_LTC
20	1.125	1.642	0.3784	0.6216	31.25	11.83	7.768	1.485
15	1.156	1.572	0.3887	0.6113	30.42	11.83	5.264	1.838
10	1.177	1.526	0.3959	0.6041	29.87	11.83	5.054	1.652
5	1.189	1.501	0.3999	0.6001	29.58	11.83	4.211	2.050
4	1.190	1.498	0.4003	0.5997	29.55	11.83	4.068	2.096
3	1.191	1.496	0.4006	0.5994	29.52	11.83	3.931	2.144
2	1.192*	1.495	0.4008	0.5992	29.51	11.83	3.801	2.192
1	1.192*	1.495	0.4008	0.5992	29.51	11.83	3.677	2.242
0	1.191	1.496	0.4007	0.5993	29.52	11.83	3.559	2.324

-1	1.191	1.497	0.4005	0.5995	29.53	11.83	3.446	2.347
-2	1.190	1.499	0.4001	0.5999	29.56	11.83	3.338	2.402
-3	1.188	1.502	0.3997	0.6003	29.59	11.83	3.235	2.459
-4	1.187	1.506	0.3991	0.6009	29.64	11.83	3.135	2.518
-5	1.184	1.510	0.3984	0.6016	29.69	11.83	3.04	2.579
-6	1.182	1.515	0.3975	0.6025	29.75	11.83	2.949	2.641
-7	1.179	1.521	0.3966	0.6034	29.82	11.83	2.862	2.706
-8	1.176	1.528	0.3955	0.6045	29.90	11.83	2.778	2.774
-9	1.173	1.536	0.3944	0.6056	29.99	11.83	2.697	2.844
-10	1.169	1.544	0.3931	0.6069	30.09	11.83	2.619	2.916
-15	1.145	1.597	0.3850	0.6150	30.72	11.83	2.271	3.325
-20	1.113	1.670	0.3745	0.6255	31.58	11.83	1.979	3.832

Table-4(d): Variation of Thermal performance with variation of cascade evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFO-134a in low temperature circuit for T_Cond=50°C with subcooling of 5°C, T_$_{\text{Eva\_HTC}}$= -10°C, T_$_{\text{Eva\_LTC}}$=-50°C, Q_$_{\text{Eva\_LTC}}$=35 “kW”

T_Eva (°C)	COP	W$_{\text{\_Comp\_HTC}}$ (kW)	W$_{\text{\_Comp\_LTC}}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of R-1234yf	Q_$_{\text{Cond \_HTC}}$ (kW)	Q_$_{\text{Cond \_Cascade}}$ (kW)	Q_$_{\text{EVA\_LTC}}$ (kW)
20	1.125	7.575	23.68	0.5130	0.2793	66.42	58.85	35.167
15	1.156	9.132	21.29	0.5057	0.2642	66.59	56.46	35.167
10	1.177	10.74	19.13	0.5004	0.2508	65.04	54.30	35.167
5	1.189	12.42	17.15	0.4968	0.2389	64.74	52.32	35.167
4	1.190	12.77	16.78	0.4962	0.2367	64.71	51.94	35.167
3	1.191	13.12	14.14	0.4957	0.2345	64.69	51.57	35.167
2	1.192	14.92	14.64	0.4941	0.2242	64.73	49.3	35.167
1	1.192	13.83	15.68	0.4949	0.2303	64.68	50.85	35.167
0	1.191	14.19	15.33	0.4946	0.2282	64.68	50.5	35.167
-1	1.191	14.55	14.98	0.4943	0.2262	64.70	50.15	35.167
-2	1.190	14.92	14.64	0.4941	0.2242	64.73	49.8	35.167
-3	1.188	14.29	14.3	0.4940	0.2223	64.76	49.47	35.167
-4	1.187	15.67	13.97	0.4938	0.2204	64.8	49.13	35.167
-5	1.184	16.05	13.64	0.4938	0.2185	64.86	48.8	35.167
-6	1.182	16.44	13.31	0.4938	0.2204	64.92	48.43	35.167
-7	1.179	16.83	12.99	0.4938	0.2167	64.99	48.16	35.167
-8	1.176	17.22	12.68	0.4939	0.2132	65.07	47.84	35.167
-9	1.173	17.62	12.37	0.494	0.2114	65.16	47.53	35.167
-10	1.169	18.03	12.06	0.4342	0.2097	65.26	47.23	35.167
-15	1.145	20.14	10.58	0.4958	0.2017	65.88	45.74	35.167
-20	1.113	22.41	9.176	0.4986	0.1943	66.75	44.34	35.167

Table-4(e): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50°C with subcooling of 5°C, T_$_{\text{Eva\_HTC}}$= 0°C, T_$_{\text{Eva\_LTC}}$=-50°C, Q_$_{\text{Eva\_LTC}}$=35 “kW”

T_Cond (°C)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\text{\_LTC}}$
25	1.716	0.7325	0.5772	0.4338	20.49	11.83	9.783	2.294
30	1.599	0.8592	0.5379	0.4621	21.99	11.83	7.581	2.294
35	1.49	0.9961	0.5010	0.4990	23.61	11.83	6.099	2.294
40	1.386	1.141	0.4661	0.5339	25.38	11.83	5.026	2.294
45	1.287	1.311	0.4328	0.5672	27.33	11.83	4.208	2.294
50	1.191	1.496	0.4007	0.5993	29.52	11.83	3.559	2.294
55	1.099	1.706	0.3695	0.6305	32.01	11.83	3.027	2.294
60	1.007	1.952	0.3388	0.6612	34.91	11.83	2.579	2.294

Table-4(f): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50°C with subcooling of 5°C, T_$_{\text{Eva\_HTC}}$= 0°C, T_$_{\text{Eva\_LTC}}$=-50°C, Q_$_{\text{Eva\_LTC}}$=35 “kW”

T_Cond (°C)	COP	$W_{\_Comp\_HTC}$ (kW)	$W_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$ (kW)	$Q_{\_EVA\_LTC}$ (kW)
25	1.716	5.162	15.33	0.3669	0.2282	55.56	50.5	35.167
30	1.599	6.661	15.33	0.3862	0.2282	57.16	50.5	35.167
35	1.49	8.28	15.33	0.4079	0.2282	58.78	50.5	35.167
40	1.386	10.05	15.33	0.4327	0.2282	60.54	50.5	35.167
45	1.287	12.0	15.33	0.4612	0.2282	62.5	50.5	35.167
50	1.191	14.19	15.33	0.4946	0.2282	64.68	50.5	35.167
55	1.099	16.68	15.33	0.5341	0.2282	67.18	50.5	35.167
60	1.007	19.58	15.33	0.5818	0.2282	70.08	50.5	35.167

Table4(g): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50°C with subcooling of 5°C, $T_{\_Eva\_HTC}$= -10°C, $T_{\_Eva\_LTC}$=-50°C, $Q_{\_Eva\_LTC}$=35 “kW”

T_Eva (°C)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\_LTC}$
-50	1.191	1.496	0.4007	0.5993	29.52	11.83	3.559	2.294
-45	1.299	1.507	0.3990	0.6010	27.06	10.8	3.559	2.622
-40	1.417	1.529	0.3954	0.6046	24.81	9.811	3.559	3.017
-35	1.546	1.565	0.3898	0.6102	22.74	8.866	3.559	3.503
-30	1.688	1.618	0.3820	0.6170	20.84	7.96	3.559	4.112
-25	1.843	1.691	0.3717	0.6283	19.08	7.09	3.559	4.899
-20	2.015	1.789	0.3584	0.3416	17.45	6.255	3.559	5.951

Table-4(h): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=50°C with subcooling of 5°C, $T_{\_Eva\_HTC}$= 0°C, $T_{\_Eva\_LTC}$=-50°C, $Q_{\_Eva\_LTC}$=35 “kW”

T_Eva (°C)	COP	$W_{\_Comp\_HTC}$ (kW)	$W_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$ (kW)	Q_EVA$_{\_LTC}$ (kW)
-50	1.191	14.19	15.33	0.4946	0.2282	64.68	50.5	35.167
-45	1.299	13.65	13.41	0.4758	0.2236	62.23	48.58	35.167
-40	1.417	13.16	11.66	11.660.4585	0.2192	59.98	46.82	35.167
-35	1.546	12.7	10.04	0.4428	0.2149	57.91	45.21	35.167
-30	1.688	12.28	8.552	0.4282	0.2109	56.0	43.72	35.167
-25	1.843	11.9	7.179	0.4148	0.2070	54.24	42.35	35.167
-20	2.015	11.54	5.91	0.4023	0.2033	52.62	41.08	35.167

System-4:Table-5(a): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=55°C with subcooling of 5°C, $T_{\_Eva\_HTC}$= -30°C, $T_{\_Eva\_LTC}$=-100°C, $Q_{\_Eva\_LTC}$=70 “kW”

T_Eva (°C)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\_LTC}$
R134a	0.4791	1.889	0.3461	0.6539	146.10	50.58	1.448	1.211
R245fa	0.4852	1.852	0.3506	0.6494	144.3	50.58	1.448	1.234
R143a	0.4719	1.933	0.3409	0.6561	148.3	50.58	1.448	1.184
R227ea	0.4517	2.064	0.3264	0.6736	155.0	50.58	1.448	1.110
R123	0.4880	1.836	0.3526	1.448	143.0	50.58	1.448	1.245

Table-5(a): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and following refrigerants in low temperature circuit for T_Cond=55°C with subcooling of 5°C, $T_{\_Eva\_HTC}$= -30°C, $T_{\_Eva\_LTC}$=-100°C, $Q_{\_Eva\_LTC}$=35 “kW”

LTC Refrigerants	COP	System EDR	Exergetic Efficiency	EDR$_{\_Rational}$	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP_LTC
R-134a	0.4791	1.889	0.3461	0.6539	73.41	25.41	1.448	1.211
R141b	0.5026	1.754	0.3632	0.6368	69.97	25.41	1.448	1.302
R-404a	0.4608	2.003	0.3330	0.6670	65.93	25.41	1.448	1.143
R-410a	0.4757	1.910	0.3437	0.6563	73.93	25.41	1.448	1.198
R-407c	0.4115	2.363	0.2973	0.7027	85.47	25.41	1.448	0.972
R-227ea	0.4517	2.064	0.3264	0.6736	77.85	25.41	1.448	1.10
R-236fa	0.4729	1.927	0.3417	0.6583	74.37	25.41	1.448	1.187
R-245fa	0.4852	1.852	0.3506	0.6494	72.48	25.41	1.448	1.234
R-32	0.4531	2.054	0.3234	0.6766	77.61	25.41	1.448	1.115
R-600a	0.4834	1.863	0.3493	0.6507	72.75	25.41	1.448	1.227
R-600	0.4906	1.821	0.3545	0.6455	71.68	25.41	1.448	1.255
R-290	0.4829	1.866	0.3489	0.6511	72.82	25.41	1.448	1.225
R-123	0.4880	1.836	0.3526	0.6474	72.06	25.41	1.448	1.245
R-125	0.4583	2.020	0.3312	0.6688	76.73	25.41	1.448	1.134

R-507a	0.4678	1.939	0.3380	0.6620	75.18	25.41	1.448	1.168

Table-5(b): Variation of Thermal performance with variation of HTC condenser temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and following refrigerants in low temperature circuit for T_Cond=55^{o}C with subcooling of 5^{o}C, T_$_{\text{Eva\_HTC}}$=-30^{o}C, T_$_{\text{Eva\_LTC}}$=-100^{o}C, Q_$_{\text{Eva\_LTC}}$=35 “kW”

LTC Refrigerants	COP	W_$_{\text{Comp\_HTC}}$ (kW)	W_$_{\text{Comp\_LTC}}$ (kW)	Mass flow rate (kg/sec) of R-1234ze	Mass flow rate (kg/sec) of LTC refrigerants	Q_Cond $_{\text{\_HTC}}$ (kW)	Q_Cond $_{\text{\_Cascade}}$ (kW)	Q_$_{\text{EVA}}$ $_{\text{\_LTC}}$ (kW)
R-134a	0.4791	44.36	29.05	0.6939	0.2158	108.6	64.22	35.167
R141b	0.5026	42.95	27.01	0.6720	0.1807	105.1	62.18	35.167
R-404a	0.4608	45.55	30.77	0.7125	0.2642	111.5	65.93	35.167
R-410a	0.4757	44.57	29.37	0.6973	0..1715	109.1	64.52	35.167
R-407c	0.4115	49.29	36.18	0.7710	0.1971	120.6	71.35	35.167
R-227ea	0.4517	46.17	31.68	0.7223	0.4154	113.0	66.84	35.167
R-236fa	0.4729	44.75	29.62	0.7001	0.3020	109.5	64.78	35.167
R-245fa	0.4852	43.98	28.5	0.6880	0.2188	107.6	63.67	35.167
R-32	0.4531	46.08	31.53	0.7208	0.1163	112.8	66.70	35.167
R-600a	0.4834	44.08	28.66	0.6897	0.1264	107.9	63.83	35.167
R-600	0.4906	43.66	28.03	0.6829	0.1191	106.9	63.2	35.167
R-290	0.4829	44.12	28.7	0.6902	0.1152	106.0	63.87	35.167
R-123	0.4880	43.81	26.25	0.6854	0.2418	107.2	63.42	35.167
R-125	0.4583	45.72	31.01	0.7152	0.3415	111.90	66.18	35.167
R-507a	0.4678	45.08	30.10	0.7053	0.2701	110.3	65.26	35.167

Table-5(c): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=55^{o}C with subcooling of 5^{o}C, T_$_{\text{Eva\_HTC}}$= -30^{o}C, T_$_{\text{Eva\_LTC}}$=-100^{o}C, Q_$_{\text{Eva\_LTC}}$=35 “kW”

T_Eva (^{o}C)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product (kW)	COP_HTC	COP$_{\text{\_LTC}}$
-100	0.4791	1.889	0.3464	0.6536	73.41	25.54	1.448	1.211
-95	0.5197	1.854	0.3504	0.6496	67.66	23.71	1.448	1.371
-90	0.5625	1.829	0.3535	0.6465	62.52	22.10	1.448	1.556
-85	0.6075	1.813	0.3554	0.6446	57.89	20.58	1.448	1.77
-84	0.6167	1.811	0.3557	0.6443	57.02	20.28	1.448	1.81
-83	0.6261	1.81	0.3559	0.6441	56.17	19.99	1.448	1.885
-82	0.6356	1.809	0.3560	0.6440	55.33	19.70	1.448	1.916
-81	0.6451	1.808	0.3561	0.6439	54.51	19.42	1.448	1.969
-80	0.6547(opt)	1.807(opt)	0.3562(opt)	0.6438(opt)	53.71(opt)	19.13	1.448	2.201(opt)
-79	0.6645(opt)	1.807(optimum)	0.3562(opt)	0.6438(opt)	52.92(opt)	18.85	1.448	2.077(opt)
-78	0.6743	1.807(opt)	0.3562(opt)	0.6438	52.15(opt)	18.58	1.448	2.134(opt)
-77	0.6842	1.808	0.3561	0.6439	51.4	18.30	1.448	2.194
-76	0.6943	1.809	0.3559	0.6441	50.65	18.03	1.448	2.256
-75	0.7044	1.811	0.3557	0.6443	49.93	17.76	1.448	2.32
-70	0.7585	1.825	0.3540	0.6460	46.49	16.46	1.448	2.679
-65	0.8113	1.849	0.3510	0.6490	43.35	15.22	1.448	3.12
-60	0.8688	1.894	0.3567	0.6433	40.48	14.03	1.448	3.674

Table-5(d): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234ze in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=55^{o}C with subcooling of 5^{o}C, T_$_{\text{Eva\_HTC}}$= -30^{o}C, T_$_{\text{Eva\_LTC}}$=-100^{o}C, Q_$_{\text{Eva\_LTC}}$=35 “kW”

T_Eva (^{o}C)	COP	W_$_{\text{Comp\_HTC}}$ (kW)	W_$_{\text{Comp\_LTC}}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate(kg/sec)of R-134a	Q_Cond $_{\text{\_HTC}}$(kW)	Q_Cond $_{\text{\_Cascade}}$ (kW)	Q_EVA$_{\text{\_LTC}}$ (kW)
-100	0.4791	44.36	29.05	0.6939	0.2158	108.60	64.22	35.167
-95	0.5197	42.01	25.65	0.6572	0.2118	102.80	60.82	35.167
-90	0.5625	39.91	22.61	0.6243	0.2080	97.69	57.78	35.167
-85	0.6075	38.02	19.87	0.6075	0.2043	93.06	55.04	35.167
-84	0.6167	37.66	19.36	0.5892	0.2036	92.19	54.52	35.167
-83	0.6261	37.32	18.85	0.5838	0.2029	91.34	54.02	35.167
-82	0.6356	36.97	18.36	0.5784	0.2021	90.05	53.53	35.167
-81	0.6451	36.64	17.87	0.5732	0.2014	89.68	53.04	35.167
-80	0.6547	36.31	17.40	0.5681	0.2007	88.88	52.57	35.167
-79	0.6645	35.99	16.93	0.5630	0.20	88.09	52.10	35.167
-78	0.6743	35.68	16.48	0.5581	0.1993	87.32	51.64	35.167

-77	0.6842	35.37	16.03	0.5533	0.1986	86.56	51.2	35.167
-76	0.6943	35.06	15.59	0.5485	0.1979	85.82	50.76	35.167
-75	0.7044	34.77	15.16	0.5439	0.1972	85.09	50.33	35.167
-70	0.7585	33.36	13.13	0.5219	0.1938	81.65	48.29	35.167
-65	0.8113	32.08	11.27	0.5018	0.1906	78.52	46.44	35.167
-60	0.8688	30.91	9.573	0.4835	0.1874	75.65	44.74	35.167

Table-5(e): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234ze in high temperature circuit and HFO1234ze Refrigerantin the low temperature circuit T_$_{\text{Cond\_HTC}}$=55^{o}C, T_$_{\text{Eva\_HTC}}$= -30^{o}C ,Approach (Temperature_$_{\text{Overlapping}}$) = 10^{o}C , T_$_{\text{Eva\_LTC}}$= -50^{o}C , Compressor _Efficiency_$_{\text{HTC}}$= 0.80, Compressor _Efficiency_$_{\text{LTC}}$=0.80,Eva=35.167 “KW”

T_Eva_HTC (ºC)	First law Efficiency (COP)	System Exergy Destruction Ratio based on output	Second Law Efficiency/ Exergetic Efficiency	High Temperature Circuit COP_$_{\text{HTC}}$	Low Temperature Circuit COP_$_{\text{LTC}}$	Exergy of fuel (kW)	Exergy of product (kW)
20	0.3958	2.497	0.2860	6.446	0.4871	88.86	25.41
15	0.4171	2.318	0.3034	5.287	0.5385	84.81	25.41
10	0.4358	2.176	0.3149	4.421	0.5928	80.70	25.41
5	0.4516	2.064	0.3263	3.75	0.6504	77.87	25.41
0	0.4646	1.979	0.3357	3.215	0.7120	75.69	25.41
-5	0.4746	1.916	0.3429	2.78	0.7781	74.10	25.41
-10	0.4895	1.874	0.3479	2.42	0.8496	73.03	25.41
-15	0.4854	1.851	0.3507	2.42	0.9273	72.44	25.41
-20	0.4863	1.846	0.3514	1.86	1.012	72.32	25.41
-25	0.4841	1.859	0.3493	1.639	1.106	72.64	25.41
-30	0.4791	1.889	0.3461	1.448	1.211	73.41	25.41

Table-5(f): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234yf in high temperature circuit and HFO1234ze Refrigerant in the low temperature circuit T_$_{\text{Cond\_HTC}}$=55^{o}C, T_$_{\text{Eva\_HTC}}$= -30^{o}C ,Approach (Temperature_$_{\text{Overlapping}}$) = 10^{o}C , T_$_{\text{Eva\_LTC}}$= -100^{o}C , Compressor _Efficiency_$_{\text{HTC}}$= 0.80, Compressor _Efficiency_$_{\text{LTC}}$=0.80,Eva=35.167 “KW”

T_Eva_HTC (ºC)	First law Efficiency (COP)	W$_{\text{\_Comp\_HTC}}$ (kW)	W$_{\text{\_Comp\_LTC}}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\text{\_HTC}}$ (kW)	Q_Cond $_{\text{Cascade}}$ (kW)	Q_Eva $_{\text{\_LTC}}$ (kW)
20	0.3958	16.66	72.2	0.8444	0.3706	124.4	107.4	35.167
15	0.4171	19.0	66.31	0.8111	0.3446	119.5	100.5	35.167
10	0.4358	21.38	59.33	0.7839	0.3222	115.9	94.49	35.167
5	0.4516	23.8	54.07	0.7618	0.3026	113.0	89.23	35.167
0	0.4646	26.3	49.39	0.7437	0.2858	110.9	84.56	35.167
-5	0.4746	28.9	45.19	0.7291	0.2708	109.3	80.36	35.167
-10	0.4895	31.64	41.39	0.7175	0.2574	108.2	76.56	35.167
-15	0.4854	34.52	37.92	0.7074	0.2454	107.6	73.09	35.167
-20	0.4863	37.68	34.74	0.7015	0.2345	107.6	69.9	35.167
-25	0.4841	40.85	31.79	0.6967	0.2247	107.8	66.96	35.167
-30	0.4791	44.36	29.05	0.6939	0.2158	108.6	64.22	35.167

Table-5(g): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234ze in high temperature circuit and HFO1234ze Refrigerantin the low temperature circuit T_$_{\text{Cond\_HTC}}$=55^{o}C, T_$_{\text{Eva\_HTC}}$= -30^{o}C ,Approach (Temperature_$_{\text{Overlapping}}$) = 10^{o}C , T_$_{\text{Eva\_LTC}}$= -100^{o}C , Compressor _Efficiency_$_{\text{HTC}}$= 0.80, Compressor _Efficiency_$_{\text{LTC}}$=0.80, Q_Eva=35.167 “KW”

Temperature Overlapping (ºC)	First law Efficiency (COP)	System Exergy Destruction Ratio based on output	Second Law Efficiency/ Exergetic Efficiency	High Temperature Circuit COP_$_{\text{HTC}}$	Low Temperature Circuit COP_$_{\text{LTC}}$	Exergy of fuel (W)	Exergy of product (W)
0	0.5410	1.558	0.3909	1.448	1.461	65.0	25.41
2	0.5280	1.621	0.3815	1.448	1.405	66.6	25.41
4	0.5153	1.686	0.3734	1.448	1.353	68.24	25.41
6	0.5030	1.752	0.3634	1.448	1.303	69.92	25.41
8	0.4909	1.819	0.3547	1.448	1.256	71.64	25.41
10	0.4791	1.889	0.3461	1.448	1.211	73.41	25.41
12	0.4675	1.96	0.3378	1.448	1.167	75.12	25.41

Table-5(h): Performance of Two stages Cascade Vapour

compression Refrigeration System with HFO R1234ze in high temperature circuit and HFC 134a Refrigerant in the low temperature circuit T_$_{\text{Cond\_HTC}}$=55^{o}C, T_$_{\text{Eva\_HTC}}$= -30^{o}C ,Approach (Temperature_$_{\text{Overlapping}}$) = 10^{o}C , T_$_{\text{Eva\_LTC}}$= -100^{o}C , Compressor _Efficiency_$_{\text{HTC}}$= 0.80, Compressor _Efficiency_$_{\text{LTC}}$=0.80,Eva=35.167 “KW”

Temperature Overlapping (ºC)	First law Efficiency (COP)	$W_{\_Comp\_HTC}$ (kW)	$W_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{Cascade}$ (kW)	Q_Eva $_{\_LTC}$ (kW)
0	0.5410	40.92	24.08	0.6402	0.20	100.2	59.24	35.167
2	0.5280	41.58	25.02	0.6504	0.2029	101.8	60.19	35.167
4	0.5153	42.25	25.99	0.6609	0.2060	103.4	61.16	35.167
6	0.5030	42.93	26.96	0.6716	0.2091	105.10	62.15	35.167
8	0.4909	43.64	28.0	0.6826	0.2134	106.8	63.17	35.167
10	0.4791	44.36	29.05	0.6939	0.2158	108.6	64.22	35.167
12	0.4675	45.10	30.12	0.7056	0.2192	110.4	65.29	35.167

Table-6(a): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=55ºC with subcooling of 5ºC, T$_{\_Eva\_HTC}$= -30ºC, T$_{\_Eva\_LTC}$=-100ºC, Q$_{\_Eva\_LTC}$=35 “kW”

T_Eva (ºC)	COP	EDR	Exergetic Efficiency	Rational EDR	Exergy of Fuel (kW)	Exergy of Product(kW)	COP_HTC	COP$_{\_LTC}$
-100	0.4548	2.043	0.3286	0.6714	77.33	25.41	3.027	0.7120
-95	0.5002	1.966	0.3372	0.6628	70.31	23.71	3.027	0.7972
-90	0.5490	1.899	0.3450	0.6550	64.04	22.10	3.027	0.8922
-85	0.6014	1.842	0.3519	0.6481	58.47	20.58	3.027	0.9985
-84	0.6124	1.832	0.3532	0.6468	57.43	20.28	3.027	1.021
-83	0.6235	1.822	0.3544	0.6456	56.4	19.99	3.027	1.045
-82	0.6347	1.812	0.3556	0.6444	55.4	19.7	3.027	1.068
-81	0.6482	1.803	0.3567	0.6433	54.42	19.42	3.027	1.093
-80	0.6578	1.794	0.3579	0.6421	53.46	19.13	3.027	1.118
-79	0.6695	1.786	0.3589	0.6411	52.52	18.85	3.027	1.144
-78	0.6815	1.778	0.360	0.640	51.6	18.58	3.027	1.170
-77	0.6936	1.77	0.3609	0.6391	50.7	18.30	3.027	1.197
-76	0.7059	1.763	0.3619	0.6381	49.82	18.03	3.027	1.225
-75	0.7183	1.756	0.3628	0.6372	48.96	17.76	3.027	1.253
-74	0.7310	1.750	0.3637	0.6363	48.11	17.50	3.027	1.282
-73	0.7438	1.744	0.3645	0.6355	47.28	17.23	3.027	1.312
-72	0.7569	1.738	0.3653	0.6347	46.46	16.97	3.027	1.343
-71	0.7701	1.732	0.3660	0.6340	45.87	16.71	3.027	1.374
-70	0.7835	1.727	0.3667	0.6333	44.88	16.46	3.027	1.406
-65	0.8536	1.707	0.3694	0.6306	41.2	15.22	3.027	1.582
-60	0.9292	1.697	0.3708	0.6292	37.85	14.03	3.027	1.784

Table-6(b): Variation of Thermal performance with variation of LTC evaporator temperature of two stage cascade vapour compression refrigeration system using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit for T_Cond=55ºC with subcooling of 5ºC, T$_{\_Eva\_HTC}$= -30ºC, T$_{\_Eva\_LTC}$=-100ºC, Q$_{\_Eva\_LTC}$=35 “kW”

T_Eva (ºC)	COP	$W_{\_Comp\_HTC}$ (kW)	$W_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{\_Cascade}$(kW)	Q_EVA$_{\_LTC}$ (kW)
-100	0.4548	27.93	49.30	0.8944	0.2858	112.50	84.56	35.167
-95	0.5002	26.19	44.11	0.8386	0.2789	105.50	79.26	35.167
-90	0.5490	24.64	39.42	0.7889	0.2724	99.22	74.59	35.167
-85	0.6014	23.25	35.22	0.7446	0.2661	93.64	70.39	35.167
-84	0.6124	22.99	34.43	0.7362	0.2648	92.60	69.60	35.167
-83	0.6235	22.74	33.67	0.7281	0.2636	91.57	68.83	35.167
-82	0.6347	22.49	32.91	0.7201	0.2624	90.57	68.08	35.167
-81	0.6482	22.25	32.18	0.7123	0.2612	89.59	67.34	35.167
-80	0.6578	22.01	31.46	0.7047	0.260	88.63	66.62	35.167
-79	0.6695	21.78	30.75	0.6972	0.2588	87.69	65.92	35.167
-78	0.6815	21.55	30.06	0.6899	0.2577	86.77	65.22	35.167
-77	0.6936	21.32	29.38	0.6936	0.2565	85.87	64.55	35.167
-76	0.7059	21.10	28.72	0.6557	0.2553	84.99	63.88	35.167
-75	0.7183	20.89	28.07	0.6689	0.2542	84.12	63.23	35.167
-74	0.7310	20.68	27.43	0.6621	0.2530	83.28	62.6	35.167
-73	0.7438	20.47	26.8	0.6555	0.2519	82.44	61.97	35.167
-72	0.7569	20.27	26.19	0.6491	0.2508	81.63	61.36	35.167
-71	0.7701	20.07	25.59	0.6427	0.2497	80.83	60.76	35.167
-70	0.7835	19.88	25.01	0.6385	0.2486	80.05	60.17	35.167
-65	0.8536	18.96	22.23	0.6072	0.2432	76.36	57.40	35.167
-60	0.9292	18.13	19.72	0.5805	0.2380	73.01	54.88	35.167

Table-6(c): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234ze in high temperature circuit and HFO1234yf Refrigerantin the low temperature circuit T$_{\_Cond\_HTC}$=55ºC, T$_{\_Eva\_HTC}$= -30ºC ,Approach (Temperature$_{\_Overlapping}$) = 10ºC , T$_{\_Eva\_LTC}$= -50ºC , Compressor _Efficiency$_{\_HTC}$= 0.80, Compressor _Efficiency$_{\_LTC}$=0.80,Eva=35.167 “KW”

T_Eva_HTC (^{o}C)	First law Efficiency (COP)	System Exergy Destruction Ratio based on output	Second Law Efficiency/ Exergetic Efficiency	High Temperature Circuit COP$_{\_HTC}$	Low Temperature Circuit COP$_{\_LTC}$	Exergy of fuel (W)	Exergy of product (W)
20	0.3969	2.526	0.2837	6.179	0.4871	89.58	25.41
15	0.4127	2.354	0.2982	5.047	0.5385	85.22	25.41
10	0.4298	2.22	0.3106	4.201	0.5928	81.82	25.41
5	0.4439	2.118	0.3207	3.547	0.6504	79.22	25.41
0	0.4548	2.043	0.3286	3.027	0.712	77.33	25.41
-5	0.4624	1.993	0.3341	2.604	0.7781	76.05	25.41
-10	0.4668	1.965	0.3373	2.255	0.8496	75.34	25.41
-15	0.4678	1.958	0.3380	1.962	0.9273	75.17	25.41
-20	0.4656	1.972	0.3364	1.714	1.012	75.52	25.41
-25	0.4603	2.007	0.3326	1.501	1.106	76.4	25.41
-30	0.4520	2.062	0.3266	1.317	1.211	77.8	25.41

Table-6(d): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234yf in high temperature circuit and HFO1234yf Refrigerant in the low temperature circuit T$_{\_Cond\_HTC}$=55^{o}C, T$_{\_Eva\_HTC}$= -30^{o}C ,Approach (Temperature$_{\_Overlapping}$) = 10^{o}C, T$_{\_Eva\_LTC}$= -100^{o}C, Compressor Efficiency$_{\_HTC}$= 0.80, Compressor _Efficiency$_{\_LTC}$=0.80,Eva=35.167 “KW”

T_Eva_HTC (^{o}C)	First law Efficiency (COP)	W$_{\_Comp\_HTC}$ (kW)	W$_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{Cascade}$ (kW)	Q_Eva $_{\_LTC}$ (kW)
20	0.3969	17.38	72.20	1.002	0.3706	124.7	107.4	35.167
15	0.4127	19.91	65.71	0.9654	0.3445	120.9	100.5	35.167
10	0.4298	22.49	59.33	0.9361	0.3222	117.0	94.49	35.167
5	0.4439	25.16	54.07	0.9128	0.3028	114.4	89.23	35.167
0	0.4548	27.93	49.39	0.8944	0.2858	112.5	84.56	35.167
-5	0.4624	30.85	45.19	0.8803	0.2708	111.2	80.35	35.167
-10	0.4668	33.93	41.39	0.870	0.2574	110.5	76.56	35.167
-15	0.4678	37.25	37.92	0.8629	0.2454	110.3	73.09	35.167
-20	0.4656	40.79	34.74	0.8590	0.2345	110.7	69.9	35.167
-25	0.4603	44.61	31.79	0.8580	0.2247	111.6	66.96	35.167
-30	0.4520	48.76	29.05	0.8598	0.2158	113.0	64.22	35.167

Table-6(e): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234ze in high temperature circuit and HFO1234yf Refrigerantin the low temperature circuit T$_{\_Cond\_HTC}$=55^{o}C, T$_{\_Eva\_HTC}$=-30^{o}C, Approach (Temperature$_{\_Overlapping}$)= 10^{o}C, T$_{\_Eva\_LTC}$= -100^{o}C, Compressor _Efficiency$_{\_HTC}$=0.80, Compressor _Efficiency$_{\_LTC}$=0.80, Eva=35.167 “kW”

Temperature Overlapping (^{o}C)	First law Efficiency (COP)	System Exergy Destruction Ratio based on output	Second Law Efficiency/ Exergetic Efficiency	High Temperature Circuit COP$_{\_HTC}$	Low Temperature Circuit COP$_{\_LTC}$	Exergy of fuel (W)	Exergy of product (W)
0	0.5093	1.718	0.3680	1.317	1.461	69.05	26.41
2	0.4993	1.783	0.3593	1.317	1.405	70.02	26.41
4	0.4856	1.85	0.3509	1.317	1.363	72.42	26.41
6	0.4741	1.919	0.3426	1.317	1.303	74.17	26.41
8	0.4630	1.989	0.3345	1.317	1.256	75.96	26.41
10	0.4548	2.043	0.3266	1.317	1.211	77.80	26.41
12	0.4413	2.136	0.3189	1.317	1.167	79.69	26.41

Table-6(f): Performance of Two stages Cascade Vapour compression Refrigeration System with HFO R1234yf in high temperature circuit and HFC 134a Refrigerant in the low temperature circuit T$_{\_Cond\_HTC}$=55^{o}C, T$_{\_Eva\_HTC}$= -30^{o}C ,Approach (Temperature$_{\_Overlapping}$) = 10^{o}C , T$_{\_Eva\_LTC}$= -100^{o}C , Compressor _Efficiency$_{\_HTC}$= 0.80, Compressor _Efficiency$_{\_LTC}$=0.80,Eva=35.167 “KW”

Temperature Overlapping (^{o}C)	First law Efficiency (COP)	W$_{\_Comp\_HTC}$ (kW)	W$_{\_Comp\_LTC}$ (kW)	Mass flow rate (kg/sec) of R-1234yf	Mass flow rate (kg/sec) of R-134a	Q_Cond $_{\_HTC}$ (kW)	Q_Cond $_{Cascade}$ (kW)	Q_Eva $_{\_HTC}$ (kW)
0	0.5093	44.98	26.06	0.7932	0.200	104.2	59.24	35.167
2	0.4993	45.70	25.02	0.8059	0.2029	105.9	60.19	35.167
4	0.4856	46.43	26.99	0.8189	0.2060	107.6	61.16	35.167
6	0.4741	47.19	26.98	0.8322	0.2091	109.3	62.15	35.167
8	0.4630	47.97	28.0	0.8458	0.2124	111.1	63.17	35.167
10	0.4548	48.75	29.05	0.8598	0.2158	113.0	64.22	35.167

12	0.4413	49.57	30.12	0.8742	0.2192	114.9	65.29	35.167

Table7: Thermal Performance of Vapour compression Refrigeration System with following Refrigerants in the low temperature circuit T_$_{Cond}$=55°C, T_$_{Evaporator}$= -30°C , Compressor _Efficiency_= 0.80, Q_Eva=70 “KW”

Refrigerants In VCR	First law Efficiency (COP)	System Exergy Destruction Ratio based on output	Second Law Efficiency/ Exergetic Efficiency	Rational EDR	Exergy of product (W)	Exergy of fuel (W)
R1234ze	1.448	2.052	0.3277	0.6723	15.84	53.14
R1234yf	1.317	2.354	0.2981	0.7019	15.84	48.36
R134a	1.508	1.930	0.3413	0.6787	15.84	46.43
R290	1.475	1.995	0.3339	0.6661	15.84	47.45
R152a	1,67	1.646	0.3779	0.6221	15.84	41.93
R717	1.718	1.572	0.3887	0.6113	15.84	40.76
R-600a	1.501	1.944	0.3396	0.6604	15.84	46.65
R-600	1.623	1.723	0.3693	0.3307	15.84	43.19
R123	1.722	1.566	0.3931	0.6069	15.84	40.65
R410a	1.409	2.137	0.3186	0.6814	15.84	49.70
R404a	1.173	2.767	0.2654	0.7346	15.84	59.69
R125	1.003	3.4	0.3541	0.6459	15.84	71.04
R407c	1.301	2.393	0.2944	0.7056	15.84	53.82

Table-8(a): Optimum Results for two stage cascade system (system-6) using HFO-1234ze in high temperature circuit using condenser temperature of 55 °C and HFC-134a in low temperature circuit using low temperature circuit evaporator temperature of (-100°C) at Optimum LTC evaporator temperature= -78 °C, -79 °C & -80°C.

Optimum Parameters	Optimum Temperature =- 78 °C	Optimum Temperature = -79 °C	Optimum Temperature = -80 °C
First law efficiency (COP_System)	0.6743	0.6645	0.6547
Exergy Destruction Ratio (EDR)	1.807	1.807	1.807
Exergy of Fuel (kW)	52.15	52.92	53.71
Exergy of Product (kW)	18.58	18.85	19.13
Total work done by HTC compressor (kW)	35.68	35.99	36.31
Total work done by LTC compressor (kW)	16.48	16.93	17.40
Mass flow rate in HTC compressor (Kg/sec)	0.5581	0.5630	0.5681
Mass flow rate in LTC compressor (Kg/sec)	0.1993	0.200	0.2007
Heating Load on cascade Condenser (KW)	51.64	52.10	52.57
Heating Load on HTC Condenser (KW)	87.32	88.09	88.88
Cooling Load on LTC Condenser (KW)	35.167	35.167	35.167
Second law efficiency (Exergetic _Efficiency)	0.3562	0.3562	0.3562
First law circuit efficiency (COP_HTC)	1.448	1.448	1.448
First law circuit efficiency (COP_LTC)	2.134	2.077	2.20

Table 8(b): Optimum Results for two stage cascade system (system-6) using HFO-1234ze in high temperature circuit using condenser temperature of 55 °C and HFC-134a in low temperature circuit using low temperature circuit evaporator temperature of (-50°C) at Optimum HTC evaporator temperature= -6 °C and -7 °C.

Optimum Parameters	Optimum emperature =-6 °C	Optimum emperature =-7 °C
First law efficiency (COP_System)	1.195	1.195
Exergy Destruction Ratio (EDR)	1.489	1.489
Exergy of Fuel (kW)	29.43	29.44
Exergy of Product (kW)	=11.83	11.83
Total work done by HTC compressor (kW)	15.71	16.06
Total work done by LTC compressor (kW)	13.73	13.38,
Mass flow rate in HTC compressor (Kg/sec)	0.4181	0.4176
Mass flow rate in LTC compressor (Kg/sec)	0.2805	0.2777
Heating Load on cascade Condenser (KW)	48.89	48.55
Heating Load on HTC Condenser (KW)	64.6	64.6
Cooling Load on LTC Condenser (KW)	35.167	35.167
Second law efficiency (Exergetic_Efficiency)	0.4018	0.4018
First law circuit efficiency (COP_HTC)	3.113	3.113
First law circuit efficiency (COP_LTC)	2.562	2.562

5.Conclusions

The following conclusions were drawn from present investigations.

(i) The Optimum Results for cascade refrigeration using R1234ze in high temperature circuit using high temperature condenser temperature (55 ºC)and R134a in low temperature circuit (system-6) of -100ºC low temperature circuit evaporator , 10ºC of temperature overlapping (Approach) and 80% high temperature circuit compressor efficiency and also 80% of low temperature circuit compressor efficiency the optimum evaporator temperature high temperature circuit (HTC) to be -78 ºC , -79 ºC & -80 ºC respectively and no optimum was found using HFO-1234yf in high temperature circuit and HFC-134a in low temperature circuit.

(ii)The Optimum Results for cascade refrigeration using R1234ze in high temperature circuit and R1234yf in low temperature circuit (system-1) using50ºC of high temperature circuit condenser temperature & -50ºC low temperature circuit evaporator , 10ºC of temperature overlapping (Approach) and 80% high temperature circuit compressor efficiency and also 80% of low temperature circuit compressor efficiency the optimum evaporator temperature high temperature circuit (HTC)to be -6 ºC and -7 ºC respectively

(iii)Up to temperature -50 ºC in the low temperature evaporator circuit with temperature overlapping (Approach=10ºC) and condenser temperature of 50 ºC with cascade evaporator of 0ºC , the combination of R1234ze in high temperature circuit and R1234yf in low temperature circuit gives best results for replacing R134a.

iv) For -100ºC of low temperature evaporator circuit and 50ºC of high temperature condenser and -30ºC cascade evaporator with temperature overlapping (Approach=10ºC) the combination of R1234ze – and R245fa gives better thermodynamic performances as compared to R-1234yf and R245fa

(v)The ecofriendly refrigerants HFO can replace R134a without minor modifications.

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