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**ORIGINAL ARTICLE**

# Thermodynamic performances of cascaded vapor compression refrigeration system using eco-friendly low GWP blends of HFC+HFO refrigerants in higher temperature cycle using blends of HFC+HFO refrigerants in low temperature cycle

**R. S. Mishra**

*Department of Mechanical Engineering, Delhi Technological University, Delhi, India.*

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## Abstract

Several alternatives are available in the literature for using HFC blends which for causing higher global warming potential without ozone depletion for replacing CFC refrigerants also have ultra-high global warming potential with ozone depletion. In this paper, thermodynamic energy-exergy performances of cascaded vapour 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 50ºC to -30ºC and also using blends of HFC+HFO refrigerants in low GWP in low temperature cycle have been investigated. It was observed that System44 gives highest thermodynamic first and second law performances. The lowest thermodynamic performances were observed by using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle in the cascaded of vapour compression refrigeration (system 41).



## 1. Introduction

In current decades many countries have rewarded more consideration to environmental pollution caused by various fuels and CFCs. Burning fossil fuels cause water vapor (H2O), carbon dioxide (CO2), methane (CH4), and sulfur dioxide (SO2) in the atmosphere to absorb radiation, leading to increased global warming. In addition, gases emitted from several industries especially containing perfluorocarbons (PFC) derivatives such as chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFC), hydrofluorocarbons (HFCs), methane (CH4), sulfur hexafluoride (SF6) etc. have also led to a more serious increase in global warming. The occurrence of gas in an atmosphere that absorbs and emits radiation within the thermal infrared range is called a greenhouse gas (GHG), whereas the comparative measure of how much heat a GHG traps in the atmosphere is defined as the Global Warming Potential (GWP). It compared the amount of heat trapped to the amount of heat trapped by $CO_2$. GHGs act as a blanket of solar radiation on the earth's surface, thus making the average global temperature. It can be fulfilled that the more GHGs produced, the higher the average global temperature. CFCs and HCFCs used by conventional refrigeration systems have a global warming potential (GWP) and have a high value of ozone-depleting potential (ODP). Biomedical specimens must achieve a storage temperature of around -80°C [1-2]. Cascade

*Corresponding author: R. S. Mishra*
*Email Address: hod.mechanical.rsm@dtu.ac.in*
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refrigeration is a method of refrigeration used to achieve temperatures below -40°C. J. Alberto Dopazo and Jose Fernandez-seara [3] designed developed a prototype of a cascade refrigeration system using NH3 and $CO_2$ as refrigerants used to supply a 9 kW refrigeration capacity horizontal plate freezer at an evaporating temperature of −50°C and performed several experimental tests by fixing four $CO_2$ evaporating temperatures and found the influence of the operating parameters on the cascade system's performance. Nasruddin et al. [4] carried out the simulation studies that a mixture of carbon dioxide and ethane can achieve the minimum temperature of -80° C of a mix of carbon dioxide and methane is an excellent alternative refrigerant. Nasruddin et al., [5] found. The best performance using carbon dioxide and propane compared to R410a and R134a, whereas R744 ($CO_2$) is flammable and a green refrigerant. Mishra [5] described thermodynamic analysis of cascade refrigeration systems with huge refrigerants, including CFC, HCFC, HFC, HFC and HFO refrigerants etc and optimizations conducted for such refrigerants. However, the trends show that the HFO refrigerants are natural refrigerants gaining more importance due to environmental conditions few natural refrigerants [3]. Exergy analysis is a useful way to determine the real thermodynamic losses and optimize environmental and economic performance in 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. In the calculation of losses occurring in different system components, besides the exergy efficiency of the refrigeration cycle and developed a computer code by using the EES-V9.172-3D software package program and computed the effect of evaporator and condenser temperatures on the exergy destruction and exergy efficiency of the system using HFO-1234yf and HFO1234ze, which are good alternatives to R134a concerning their environmentally friendly properties. By cascading more than two VCR stages, Mishra R.S. [8] numerically computed thermodynamic performances by using an evaporator the temperature in a low-temperature cycle ranges from -145°C to -155°C by HFO-1336mzz(Z) and up to -160°C by HFO-1225ye(Z) refrigerants and using hydrocarbons in LTC. The optimal cascade vapor compression refrigeration system with multiple blended refrigerants and multiple temperature levels presents considerable challenges, and systematic studies are still lacking. In this paper, the optimal HFO +HFC blends of such cascaded vapor compression refrigeration systems to maximize the energy & exergy efficiencies have been presented.

## 2. Use of HFC+HFO Blends in Cascaded VCRs.

Cascaded vapor compression refrigeration systems are essential to chemical/petrochemical process industries because their thermodynamic performances are closely related to product quality and plant profitability previously.

Adrián Mota-Babiloni [9] carried out the analysis of the feasibility of R454C and R455A, two new low global warming potential (GWP of 148) refrigerants, in vapor compression refrigeration systems as alternatives to R404A for warm countries and found that the R454C and R455A will be the most viable low GWP options to perform a direct replacement of R404A due to similar uniqueness and found experimental results show that the cooling capacity of the replacements is slightly lower than R404A, being the Coefficient of Performance (COP) of the new mixtures 10–15% higher than that of R404A, especially at higher condensation. The thermodynamic energy& exergy performances of vapor compression using nine blends have also been investigated in this paper.

## 3. Results and Discussion

Following Cascaded vapour compression refrigerations have been considered for numerical computations.

System-1: Cascaded vapour 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, $T\_{cond}$=50°C, T_ambient=25°C, $T\_{Eva\_HTC}$=-30°C , $T\_{Eva\_LTC}$=-90°C, Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%. Compressor $efficiency\_{LTC}$=80%.

System-2: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R454B low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50°C, T_ambient=25°C, $T\_{Eva\_HTC}$=-30°C, $T\_{Eva\_LTC}$=-90°C, Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%. Compressor $efficiency\_{LTC}$=80%

System- 3: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R454C low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50°C, T_ambient=25°C, $T\_{Eva\_HTC}$=-30°C, $T\_{Eva\_LTC}$=-90°C, Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%, Compressor $efficiency\_{LTC}$=80%.

System-4: Cascaded vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50°C, T_ambient=25°C, $T\_{Eva\_HTC}$=-30°C, $T\_{Eva\_LTC}$=-90°C, Temperature overlapping=10, Compressor $efficiency\_{HTC}$=80%, Compressor $efficiency\_{LTC}$=80%.

System-5: Cascaded thermodyamic performances of vapour 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 vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R454B 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 t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R454C 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 vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R449A 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-9: Cascaded thermodyamic performances of vapour 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- 10: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R454B 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-11: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R454C 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-12: Cascaded thermodyamic performances of vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R449A 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- 13: Cascaded t hermodynamic performances of vapour 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- 14: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R454B low GWP refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-0ºC, Temperature overlapping=10, Compressor $efficiency_{\_HTC}$=80%. Compressor $efficiency_{\_LTC}$=80%.

System- 15: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R454C 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- 16: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-0ºC, Temperature overlapping=10, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_LTC}$=80%.

Table-2(a)-Table-2(b) show the comparison of first law efficiency ($COP_{\_Cascade}$) of cascaded vapour compression refrigeration systems using HFC +HFO Blends in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration system-13 using R454B in high temperature cycle and R513A in low temperature cycle gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration system-14 using R452A in high temperature cycle and R449A in low temperature cycle gives lower first law efficiency (COP_$_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio. Although cascaded vapour compression refrigeration system--1 using R450A in high temperature cycle and R513A in low temperature cycle gives slightly lower first law efficiency (COP_$_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio than system-4.

*Table-2(a) Thermodynamic performances of cascaded vapour compression refrigeration system for ultra-low temperature applications using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly 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$_{_Eva_LTC}$=-90ºC*

| Cascaded VCRS | System: 1 | System 2 | System 3 | System 4 | System 5 | System 6 | System 7 | System 8 |
|---|---|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | R450A | R450A | R450A | R450A | R448a | R448a | R448a | R448a |
| HFC +HFO Blends in LTC | R513A | R454B | R454C | R449a | R513A | R454B | R454C | R449a |
| First Law Cascaded Efficiency COP_$_{Cascade}$ | 0.5524 | 0.5321 | 0.5053 | 0.5051 | 0.5342 | 0.5148 | 0.4892 | 0.4890 |
| Cascade Exergy Destruction Ratio(EDR_$_{Cascade}$) | 1.883 | 1.993 | 2.184 | 2.153 | 1.981 | 2.094 | 2.256 | 2.257 |
| Cascaded Exergetic Efficiency | 0.3460 | 0.3341 | 0.3174 | 0.3172 | 0.3355 | 0.3232 | 0.3071 | 0.3070 |
| Exergy of Fuel "kW" | 63.66 | 66.09 | 69.58 | 69.62 | 65.83 | 68.32 | 71.89 | 71.91 |
| Exergy of Product "kW" | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 |
| HTC Mass flow Rate (Kg/sec) | 0.6067 | 0.6216 | 0.6430 | 0.6432 | 0.5174 | 0.5301 | 0.5484 | 0.5485 |
| LTC Mass flow Rate (Kg/sec) | 0.2440 | 0.1413 | 0.2184 | 0.2021 | 0.2440 | 0.1413 | 0.2183 | 0.2021 |
| W$_{_comp\ _HTC}$"kW" | 40.88 | 41.89 | 43.33 | 43.35 | 43.04 | 44.11 | 45.63 | 45.64 |
| W$_{_comp_LTC}$ "kW" | 22.78 | 24.20 | 26.25 | 26.25 | 22.78 | 24.21 | 26.25 | 26.27 |
| Q$_{_Cond_HTC}$ "kW" | 98.83 | 101.30 | 104.70 | 104.80 | 101.0 | 103.5 | 107.1 | 107.1 |
| Q$_{_Cond_LTC}$ "kW" | 57.95 | 59.37 | 61.42 | 61.44 | 57.95 | 59.38 | 61.43 | 61.44 |
| Q$_{_Eva_HTC}$ "kW" | 57.95 | 59.37 | 61.42 | 61.44 | 57.95 | 59.38 | 61.43 | 61.44 |
| Q$_{_Eva_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 1.544 | 1.453 | 1.340 | 1.338 | 1.544 | 1.452 | 1.339 | 1.338 |
| First Law HTC Efficiency COP_$_{HTC}$ | 1.417 | 1.417 | 1.417 | 1.417 | 1.346 | 1.346 | 1.346 | 1.346 |
| HTCExergy Destruction Ratio(EDR_$_{HTC}$) | 2.199 | 2.199 | 2.199 | 2.199 | 2.284 | 2.284 | 2.284 | 2.284 |
| HTC Exergetic Efficiency | 0.3206 | 0.3206 | 0.3206 | 0.3206 | 0.3045 | 0.3045 | 0.3045 | 0.3045 |
| HTC Exergy of Fuel "kW" | 40.88 | 41.89 | 43.33 | 43.35 | 43.04 | 44.11 | 45.63 | 45.64 |
| HTC Exergy of Product "kW" | 13.11 | 13.11 | 13.11 | 13.11 | 13.11 | 13.43 | 13.90 | 13.90 |

*Table-2(b) Thermodynamic performances of vapour compression refrigeration system for ultra-low temperature applications using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly 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$_{_Eva_LTC}$=-90ºC*

| Cascaded VCRS | System: 9 | System 10 | System 11 | System 12 | System 13 | System 14 | System 15 | System 16 |
|---|---|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | R452A | R452A | R452A | R452A | R452B | R452B | R452B | R452B |
| HFC +HFO Blends in LTC | R513A | R454B | R454C | R449A | R513A | R454B | R454C | R449a |
| First Law Cascaded Efficiency COP_$_{Cascade}$ | 0.4751 | 0.4584 | 0.4364 | 0.4363 | 0.5642 | 0.5432 | 0.5157 | 0.5156 |
| Cascade Exergy Destruction Ratio(EDR_$_{Cascade}$) | 2.352 | 2.474 | 2.649 | 2.650 | 1.823 | 1.932 | 2.088 | 2.089 |
| Cascaded Exergetic Efficiency | 0.2983 | 0.2878 | 0.274 | 0.2740 | 0.3542 | 0.3411 | 0.3238 | 0.3237 |
| Exergy of Fuel "kW" | 74.02 | 76.72 | 80.58 | 80.60 | 62.34 | 64.74 | 68.19 | 68.21 |
| Exergy of Product "kW" | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 |
| HTC Mass flow Rate (Kg/sec) | 0.8286 | 0.8490 | 0.8784 | 0.8785 | 0.3605 | 0.3694 | 0.3821 | 0.3822 |
| LTC Mass flow Rate (Kg/sec) | 0.2440 | 0.1413 | 0.2183 | 0.2021 | 0.2440 | 0.1413 | 0.2183 | 0.2021 |
| W$_{_comp\ _HTC}$"kW" | 51.24 | 52.50 | 54.32 | 54.33 | 39.55 | 40.53 | 41.93 | 41.94 |
| W$_{_comp_LTC}$ "kW" | 22.78 | 24.21 | 26.26 | 26.27 | 22.78 | 24.21 | 26.26 | 26.27 |
| Q$_{_Cond_HTC}$ "kW" | 109.2 | 111.9 | 115.7 | 115.8 | 97.5 | 99.91 | 103.4 | 103.4 |
| Q$_{_Cond_LTC}$ "kW" | 57.95 | 59.38 | 61.43 | 61.44 | 57.95 | 59.38 | 61.43 | 61.44 |
| Q$_{_Eva_HTC}$ "kW" | 57.95 | 59.38 | 61.43 | 61.44 | 57.95 | 59.38 | 61.43 | 61.44 |
| Q$_{_Eva_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 1.544 | 1.452 | 1.339 | 1.338 | 1.544 | 1.452 | 1.339 | 1.338 |
| First Law HTC Efficiency COP_$_{HTC}$ | 1.131 | 1.131 | 1.131 | 1.131 | 1.465 | 1.465 | 1.465 | 1.465 |
| HTCExergy Destruction Ratio(EDR_$_{HTC}$) | 2.352 | 2.352 | 2.352 | 2.352 | 2.017 | 2.017 | 2.017 | 2.017 |
| HTC Exergetic Efficiency | 0.2588 | 0.2588 | 0.2588 | 0.2588 | 0.3314 | 0.3314 | 0.3314 | 0.3314 |
| HTC Exergy of Fuel "kW" | 51.24 | 52.50 | 54.32 | 54.33 | 39.55 | 40.53 | 41.93 | 41.93 |
| HTC Exergy of Product "kW" | 13.11 | 13.11 | 13.90 | 13.90 | 13.11 | 13.43 | 13.90 | 13.90 |

System-17: Cascaded vapour 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, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-18: Cascaded thermodyamic performances of vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R454B low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%

System- 19: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R454C low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-20: Cascaded vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-21: Cascaded thermodyamic performances of vapour compression refrigeration system using ecofriendly low GWP 450A refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%

System- 22: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP 450A refrigerants in higher temperature cycle using ecofriendly R452A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System- 23: Cascaded t hermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP 450A 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, $T\_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

Table-3(a) shows the comparison of first law efficiency ($COP\_{Cascade}$) of cascaded vapour compression refrigeration systems using R450A in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration system using R450A in high temperature cycle and R513a in low temperature cycle (system-17) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration System (system-19) using R450A in high temperature cycle and R454C in low temperature cycle gives lower first law efficiency ($COP\_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

System-24: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R513a refrigerants in higher temperature cycle using ecofriendly R454B low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC , $T\_{Eva\_LTC}$=-75ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-25: Cascaded vapour compression refrigeration system using ecofriendly low GWP R513A refrigerants in higher temperature cycle using ecofriendly low GWP R454C refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC , $T\_{Eva\_LTC}$=-75ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-26: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R513a refrigerants in higher temperature cycle using ecofriendly R448a low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC , $T\_{Eva\_LTC}$=-75ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-27: Cascaded vapour compression refrigeration system using ecofriendly low GWP R513A refrigerants in higher temperature cycle using ecofriendly low GWP R449A refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T\_{cond}$=50ºC, T_ambient=25ºC, $T\_{Eva\_HTC}$=-30ºC , $T\_{Eva\_LTC}$=-75ºC, Temperature overlapping=10, Compressor efficiency$_{HTC}$=80%. Compressor efficiency$_{LTC}$=80%.

System-28: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R513a refrigerants in higher temperature cycle using ecofriendly R452a low GWP refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-75ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

System-29: Cascaded vapour compression refrigeration system using ecofriendly low GWP R513A refrigerants in higher temperature cycle using ecofriendly low GWP R452A refrigerant in low temperature cycle ($Q\_Eva_{\_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-75ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

Table-3(b) shows the comparison of first law efficiency ($COP_{\_Cascade}$) of cascaded vapour compression refrigeration systems using R513A in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration systems using R513A in high temperature cycle and R454B in low temperature cycle (System-29$^{th}$) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using R513A in high temperature cycle and R454C in low temperature cycle(system-25$^{th}$) gives lower first law efficiency ($COP_{\_Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

*Table-3(a) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly 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.*

| Cascaded VCRS | System 17 | System 18 | System 19 | System 20 | System 21 | System 22 | System 23 |
|---|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | *R450A* | *R450A* | *R450A* | *R450A* | *R450A* | *R450A* | *R450A* |
| HFC +HFO Blends in LTC | R513a | R454b | R454C | R448a | R449a | R452a | R452b |
| First Law Cascaded Efficiency $COP_{\_Cascade}$ | 0.7425 | 0.7228 | 0.6791 | 0.6859 | 0.6885 | 0.6947 | 0.7350 |
| Cascade Exergy Destruction Ratio | 1.680 | 1.959 | 2.149 | 2.118 | 2.106 | 2.078 | 1.909 |
| Cascaded Exergetic Efficiency | 0.3472 | 0.3380 | 0.3176 | 0.3208 | 0.3220 | 0.3248 | 0.3437 |
| Exergy of Fuel “kW” | 47.36 | 48.66 | 51.79 | 51.27 | 51.08 | 50.63 | 47.35 |
| Exergy of Product “kW” | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 | 22.08 |
| HTC Mass flow Rate (Kg/sec) | 0.5066 | 0.5146 | 0.5338 | 0.5306 | 0.5294 | 0.5266 | 0.5096 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.1353 | 0.2023 | 0.1888 | 0.1885 | 0.2461 | 0.1369 |
| $W_{\_comp\_HTC}$“kW” | 34.12 | 34.67 | 35.97 | 35.76 | 35.57 | 35.49 | 34.64 |
| $W_{\_comp\_LTC}$ “kW” | 13.22 | 13.98 | 15.82 | 15.51 | 15.40 | 15.14 | 13.51 |
| $Q_{\_Cond\_HTC}$ “kW” | 82.53 | 83.82 | 86.95 | 86.44 | 86.24 | 85.79 | 83.01 |
| $Q_{\_Cond\_LTC}$ “kW” | 48.39 | 49.15 | 50.98 | 50.68 | 50.57 | 50.30 | 48.67 |
| $Q_{\_Eva\_HTC}$ “kW” | 48.39 | 49.15 | 50.98 | 50.68 | 50.57 | 50.30 | 48.67 |
| $Q_{\_Eva\_LTC}$ “kW” | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.660 | 2.515 | 2.223 | 2.267 | 2.284 | 2.323 | 2.604 |
| First Law HTC Efficiency $COP_{\_HTC}$ | 1.417 | 1.417 | 1.417 | 1.417 | 1.417 | 1.417 | 1.417 |
| HTCExergy Destruction Ratio($EDR_{\_HTC}$) | 2.199 | 2.199 | 2.199 | 2.199 | 2.199 | 2.199 | 2.199 |
| HTC Exergetic Efficiency | 0.3206 | 0.3206 | 0.3206 | 0.3206 | 0.3206 | 0.3206 | 0.3206 |
| HTC Exergy of Fuel “kW” | 34.14 | 34.67 | 36.97 | 35.76 | 35.57 | 35.49 | 34.34 |
| HTC Exergy of Product “kW” | 10.95 | 11.12 | 11.53 | 11.45 | 11.44 | 15.14 | 11.01 |

*Table-3(b) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP* R513A *refrigerants in higher temperature cycle using ecofriendly 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:24 | System25 | System:26 | System27 | System28 | System29 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | R513A | R513A | R513A | R513A | R513A | R513A |
| HFC +HFO Blends in LTC | R454B | R454C | R448a | R449a | R452a | R452b |
| First Law Cascaded Efficiency $COP_{\_Cascade}$ | 0.7093 | 0.6868 | 0.6735 | 0.6760 | 0.6820 | 0.7213 |
| Cascade Exergy Destruction Ratio($EDR_{\_Cascade}$) | 2.015 | 2.207 | 2.175 | 2.163 | 2.136 | 1.965 |
| Cascaded Exergetic Efficiency | 0.3371 | 0.3118 | 0.3149 | 0.3161 | 0.3189 | 0.3373 |
| Exergy of Fuel “kW” | 49.58 | 52.74 | 52.22 | 52.02 | 51.57 | 48.76 |
| Exergy of Product “kW” | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.5708 | 0.5921 | 0.5886 | 0.5873 | 0.5842 | 0.5653 |
| LTC Mass flow Rate (Kg/sec) | 0.1353 | 0.2023 | 0.1888 | 0.1885 | 0.2461 | 0.1359 |
| $W_{\_comp\_HTC}$“kW” | 35.59 | 36.92 | 36.70 | 36.92 | 36.43 | 35.25 |
| $W_{\_comp\_LTC}$ “kW” | 13.98 | 15.82 | 15.51 | 15.40 | 15.14 | 13.51 |
| $Q_{\_Cond\_HTC}$ “kW” | 84.74 | 87.91 | 87.39 | 87.19 | 86.73 | 83.92 |
| $Q_{\_Cond\_LTC}$ “kW” | 49.15 | 50.98 | 50.68 | 50.57 | 50.30 | 48.67 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $Q_{Eva\_HTC}$ “kW” | 49.15 | 50.98 | 50.68 | 50.57 | 50.30 | 48.67 |
| $Q_{Eva\_LTC}$ “kW” | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.515 | 2.283 | 2.267 | 2.284 | 2.323 | 2.604 |
| First Law HTC Efficiency $COP_{HTC}$ | 1.381 | 1.381 | 1.381 | 1.381 | 1.381 | 1.381 |
| HTCExergy 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” | 35.59 | 36.92 | 36.70 | 36.62 | 35.49 | 35.25 |
| HTC Exergy of Product “kW” | 11.12 | 11.53 | 11.46 | 11.44 | 15.14 | 11.01 |

System-30: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454B 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, $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-31: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R454B refrigerants in higher temperature cycle using ecofriendly R452A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC, $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-32: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R454B 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, $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-33: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454B refrigerants in higher temperature cycle using ecofriendly R448a low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-34: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R454B refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-35: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454B refrigerants in higher temperature cycle using ecofriendly R454C low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

Table-3(c) shows the comparison of first law efficiency ($COP_{Cascade}$) of cascaded vapour compression refrigeration systems using R454B in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration system (system-30) using R454B in high temperature cycle and R513A in low temperature cycle gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using R454B in high temperature cycle and R454C in low temperature cycle(system-31) gives lower first law efficiency ($COP_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

System-36: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454C 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 , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-37: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly R454B low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-38: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-39: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-

70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

System-40: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly R452A low GWP refrigerant in low temperature cycle (Q_Eva_$_{LTC}$=35.167 kW, T_$_{cond}$=50ºC, T_ambient=25ºC, T_$_{Eva_HTC}$=-30ºC , T_$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

System-41: Cascaded vapour compression refrigeration system using ecofriendly low GWP R454C 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_$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

*Table-3(c) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP* R454B *refrigerants in higher temperature cycle using ecofriendly 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%.*

| Cascaded VCRS | System:30 | System31 | System:32 | System33 | System34 | System35 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | R454B | R454B | R454B | R454B | R454B | R454B |
| HFC +HFO Blends in LTC | R513a | R454C | R448a | R449a | R452a | R452b |
| First Law Cascaded Efficiency COP_ $_{Cascade}$ | 0.7487 | 0.6845 | 0.6914 | 0.6941 | 0.7002 | 0.7411 |
| Cascade Exergy Destruction Ratio(EDR_ $_{Cascade}$) | 1.856 | 2.124 | 2.093 | 2.081 | 2.054 | 1.886 |
| Cascaded Exergetic Efficiency | 0.3501 | 0.3201 | 0.3233 | 0.3246 | 0.3275 | 0.3415 |
| Exergy of Fuel “kW” | 46.97 | 51.38 | 50.86 | 50.67 | 50.22 | 47.45 |
| Exergy of Product “kW” | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.3035 | 0.3198 | 0.3199 | 0.3172 | 0.3155 | 0.3053 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.2023 | 0.1888 | 0.1885 | 0.2461 | 0.1359 |
| W_$_{comp\ _HTC}$“kW” | 33.75 | 35.56 | 35.35 | 35.27 | 35.08 | 33.95 |
| W_$_{comp_LTC}$ “kW” | 13.22 | 15.82 | 15.51 | 15.40 | 15.14 | 13.51 |
| Q_$_{Cond_HTC}$ “kW” | 82.14 | 86.54 | 86.03 | 85.84 | 85.39 | 82.62 |
| Q_$_{Cond_LTC}$ “kW” | 48.39 | 50.98 | 50.68 | 50.57 | 50.30 | 48.67 |
| Q_$_{Eva_HTC}$ “kW” | 48.39 | 50.98 | 50.68 | 50.57 | 50.30 | 48.67 |
| Q_$_{Eva_LTC}$ “kW” | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.66 | 2.223 | 2.267 | 2.284 | 2.323 | 2.604 |
| First Law HTC Efficiency COP_ $_{HTC}$ | 1.434 | 1.434 | 1.434 | 1.434 | 1.434 | 1.434 |
| HTCExergy Destruction Ratio(EDR_$_{HTC}$) | 2.083 | 2.083 | 2.083 | 2.083 | 2.083 | 2.083 |
| HTC Exergetic Efficiency | 0.3243 | 0.3243 | 0.3243 | 0.3243 | 0.3243 | 0.3243 |
| HTC Exergy of Fuel “kW” | 33.75 | 35.56 | 35.35 | 35.27 | 35.08 | 33.95 |
| HTC Exergy of Product “kW” | 10.95 | 11.53 | 11.46 | 11.44 | 15.38 | 11.01 |

Table-3(d) shows the comparison of first law efficiency (COP_$_{Cascade}$) of cascaded vapour compression refrigeration systems using *R454C* in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration systems using *R454C* in high temperature cycle and R513A in low temperature cycle (system-36) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using *R454C* in high temperature cycle and R448A in low temperature cycle(system-38) gives lower first law efficiency (COP_$_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio .

System-42: Cascaded thermodyamic performances of vapour 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_$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

System-43: Cascaded vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly low GWP R454B 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, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

System-44: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R454C low GWP refrigerant in low temperature cycle (Q_Eva_$_{LTC}$=35.167 kW, T_$_{cond}$=50ºC, T_ambient=25ºC, T_$_{Eva_HTC}$=-30ºC , T_$_{Eva_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

System-45: Cascaded vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC , $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-46: Cascaded vapour compression refrigeration system using ecofriendly low GWP R448A refrigerants in higher temperature cycle using ecofriendly R452A low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{Eva\_HTC}$=-30ºC, $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-47: Cascaded vapour compression refrigeration system using ecofriendly low GWP R448A 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, $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

Table-3(e) shows the comparison of first law efficiency ($COP_{Cascade}$) of cascaded vapour compression refrigeration systems using R448A in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration systems using R448A in high temperature cycle and R513A in low temperature cycle(system-42) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using R448A in high temperature cycle and R452A in low temperature cycle(system-44) gives lower first law efficiency ($COP_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

*Table-3(d) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly 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:36 | System37 | System:38 | System39 | System40 | System41 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | *R454C* | *R454C* | *R454C* | *R454C* | *R454C* | *R454C* |
| HFC +HFO Blends in LTC | R513a | R454B | R448a | R449a | R452a | R452b |
| First Law Cascaded Efficiency $COP_{Cascade}$ | 0.6709 | 0.6538 | 0.6217 | 0.6240 | 0.6293 | 0.6644 |
| Cascade Exergy Destruction Ratio($EDR_{Cascade}$) | 2.187 | 2.271 | 2.439 | 2.427 | 2.398 | 2.214 |
| Cascaded Exergetic Efficiency | 0.3138 | 0.3059 | 0.2937 | 0.2918 | 0.2943 | 0.3107 |
| Exergy of Fuel "kW" | 52.41 | 53.79 | 56.53 | 56.36 | 55.88 | 52.93 |
| Exergy of Product "kW" | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.4979 | 0.5057 | 0.5215 | 0.5203 | 0.5176 | 0.5009 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.1353 | 0.1888 | 0.1885 | 0.2461 | 0.1359 |
| $W_{comp\_HTC}$"kW" | 39.19 | 39.81 | 41.05 | 40.96 | 40.74 | 39.42 |
| $W_{comp\_LTC}$ "kW" | 13.22 | 13.98 | 15.51 | 15.40 | 15.14 | 13.51 |
| $Q_{Cond\_HTC}$ "kW" | 87.58 | 88.96 | 91.73 | 91.52 | 91.05 | 88.10 |
| $Q_{Cond\_LTC}$ "kW" | 48.39 | 49.15 | 50.68 | 50.57 | 50.30 | 48.67 |
| $Q_{Eva\_HTC}$ "kW" | 48.39 | 49.15 | 50.68 | 50.57 | 50.30 | 48.67 |
| $Q_{Eva\_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.660 | 2.515 | 2.267 | 2.284 | 2.323 | 2.604 |
| First Law HTC Efficiency $COP_{HTC}$ | 1.235 | 1.235 | 1.235 | 1.235 | 1.235 | 1.235 |
| HTCExergy Destruction Ratio($EDR_{HTC}$) | 2.581 | 2.581 | 2.581 | 2.581 | 2.581 | 2.581 |
| HTC Exergetic Efficiency | 0.2793 | 0.2793 | 0.2793 | 0.2793 | 0.2793 | 0.2793 |
| HTC Exergy of Fuel "kW" | 39.19 | 39.81 | 41.05 | 40.96 | 40.74 | 39.42 |
| HTC Exergy of Product "kW" | 10.95 | 11.12 | 11.45 | 11.44 | 11.38 | 11.01 |

System-48: Cascaded thermodyamic performances of vapour 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, $T_{Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-49: Cascaded vapour compression refrigeration system using ecofriendly low GWP R449A refrigerants in higher temperature cycle using ecofriendly low GWP R454B 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, Temperature overlapping=10, Compressor $efficiency_{HTC}$=80%. Compressor $efficiency_{LTC}$=80%.

System-50: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R449A refrigerants in higher temperature cycle using ecofriendly R454C low GWP refrigerant in low temperature cycle ($Q\_Eva_{LTC}$=35.167 kW, $T_{cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

System-51: Cascaded vapour compression refrigeration system using ecofriendly low GWP R449A refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

System-52: Cascaded vapour compression refrigeration system using ecofriendly low GWP R449A refrigerants in higher temperature cycle using ecofriendly R449A low GWP refrigerant in low temperature cycle (Q_Eva$_{_LTC}$=35.167 kW, $T_{\_cond}$=50ºC, T_ambient=25ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

System-53: Cascaded vapour compression refrigeration system using ecofriendly low GWP R449A 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, $T_{\_Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

Table-3(f) shows the comparison of first law efficiency (COP$_{_Cascade}$) of cascaded vapour compression refrigeration systems using R449A in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration systems using R449A in high temperature cycle and R513A in low temperature cycle (system-48) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using R449A in high temperature cycle and R454C in low temperature cycle (system-50) gives lower first law efficiency (COP$_{_Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

*Table-3(e) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R449A refrigerants in higher temperature cycle using ecofriendly 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:42 | System43 | System:44 | System45 | System46 | System47 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in HTC | *R448A* | *R448A* | *R448A* | *R448A* | *R448A* | *R448A* |
| HFC +HFO Blends in LTC | R513A | R454B | R454C | R449A | R452a | R452b |
| First Law Cascaded Efficiency COP$_{_Cascade}$ | 0.7153 | 0.6965 | 0.6550 | 0.6640 | 0.6698 | 0.7081 |
| Cascade Exergy Destruction Ratio(EDR$_{_Cascade}$) | 1.99 | 2.070 | 2.265 | 2.220 | 2.192 | 2.020 |
| Cascaded Exergetic Efficiency | 0.3345 | 0.3257 | 0.3063 | 0.3105 | 0.3132 | 0.3312 |
| Exergy of Fuel "kW" | 49.17 | 50.49 | 53.69 | 52.96 | 52.50 | 49.66 |
| Exergy of Product "kW" | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.4320 | 0.4388 | 0.4552 | 0.4515 | 0.4491 | 0.4345 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.1353 | 0.2023 | 0.1885 | 0.2461 | 0.1359 |
| W$_{_comp\ _HTC}$"kW" | 35.94 | 36.51 | 37.87 | 37.56 | 37.36 | 36.15 |
| W$_{_comp_LTC}$ "kW" | 13.22 | 13.98 | 15.82 | 15.40 | 15.14 | 13.51 |
| Q$_{_Cond_HTC}$ "kW" | 84.33 | 85.66 | 88.86 | 88.13 | 87.67 | 84.83 |
| Q$_{_Cond_LTC}$ "kW" | 48.39 | 49.15 | 50.98 | 50.57 | 50.30 | 48.67 |
| Q$_{_Eva_HTC}$ "kW" | 48.39 | 49.15 | 50.98 | 50.57 | 50.30 | 48.67 |
| Q$_{_Eva_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.660 | 2.515 | 2.223 | 2.284 | 2.323 | 2.604 |
| First Law HTC Efficiency COP$_{_HTC}$ | 1.346 | 1.346 | 1.346 | 1.346 | 1.346 | 1.346 |
| HTCExergy Destruction Ratio(EDR$_{_HTC}$) | 2.284 | 2.284 | 2.284 | 2.284 | 2.284 | 2.284 |
| HTC Exergetic Efficiency | 0.3045 | 0.3045 | 0.3045 | 0.3045 | 0.3045 | 0.3045 |
| HTC Exergy of Fuel "kW" | 35.94 | 36.51 | 37.87 | 37.56 | 37.36 | 36.15 |
| HTC Exergy of Product "kW" | 10.95 | 11.12 | 11.53 | 11.44 | 11.38 | 11.01 |

System-54: Cascaded thermodyamic performances of vapour 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, $T_{\_Eva\_LTC}$=-70ºC, Temperature overlapping=10, Compressor efficiency$_{_HTC}$=80%. Compressor efficiency$_{_LTC}$=80%.

System-55: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly low GWP R454B 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%.

System56: Cascaded thermodynamic performances of vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R454C low GWP 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%.

System-57: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R448A low GWP 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%.

System-58: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R449A low GWP 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%.

System-59: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R452B low GWP 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%.

Table-3(g) shows the comparison of first law efficiency ($COP\_{Cascade}$) of cascaded vapour compression refrigeration systems using R452A in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration systems using R452A in high temperature cycle and R513A in low temperature cycle (system-54) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using R452A in high temperature cycle and R452A in low temperature cycle (system-56) gives lower first law efficiency ($COP\_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

*Table-3(f) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) 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%.*

| Cascaded VCRS | System:48 | System49 | System:50 | System51 | System52 | System53 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in LTC | R449A | R449A | R449A | R449A | R449A | R449A |
| HFC +HFO Blends in LTC | R513A | R454B | R454C | R448A | R452A | R452A |
| First Law Cascaded Efficiency $COP\_{Cascade}$ | 0.6969 | 0.6788 | 0.6387 | 0.6450 | 0.6530 | 0.690 |
| Cascade Exergy Destruction Ratio($EDR\_{Cascade}$) | 2.069 | 2.150 | 2.348 | 2.315 | 2.275 | 2.099 |
| Cascaded Exergetic Efficiency | 0.3259 | 0.3174 | 0.2987 | 0.3016 | 0.3054 | 0.3227 |
| Exergy of Fuel "kW" | 50.46 | 51.81 | 55.06 | 54.52 | 53.85 | 50.97 |
| Exergy of Product "kW" | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.4575 | 0.4646 | 0.4820 | 0.4791 | 0.4755 | 0.4601 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.1353 | 0.2023 | 0.1888 | 0.2461 | 0.1359 |
| $W\_{comp\_HTC}$"kW" | 37.24 | 37.83 | 39.24 | 39.01 | 38.72 | 37.46 |
| $W\_{comp\_LTC}$ "kW" | 13.22 | 13.98 | 15.82 | 15.51 | 15.14 | 13.51 |
| $Q\_{Cond\_HTC}$ "kW" | 85.63 | 86.988 | 90.22 | 89.69 | 89.02 | 86.13 |
| $Q\_{Cond\_LTC}$ "kW" | 48.39 | 49.15 | 50.98 | 50.68 | 50.30 | 48.67 |
| $Q\_{Eva\_HTC}$ "kW" | 48.39 | 49.15 | 50.98 | 50.68 | 50.30 | 48.67 |
| $Q\_{Eva\_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.660 | 2.515 | 2.223 | 2.267 | 2.323 | 2.604 |
| First Law HTC Efficiency $COP\_{HTC}$ | 1.299 | 1.299 | 1.299 | 1.299 | 1.299 | 1.299 |
| HTCExergy Destruction Ratio($EDR\_{HTC}$) | 2.402 | 2.402 | 2.402 | 2.402 | 2.402 | 2.402 |
| HTC Exergetic Efficiency | 0.2939 | 0.2939 | 0.2939 | 0.2939 | 0.2939 | 0.2939 |
| HTC Exergy of Fuel "kW" | 37.24 | 37.83 | 39.24 | 39.01 | 38.72 | 37.46 |
| HTC Exergy of Product "kW" | 10.95 | 11.12 | 11.63 | 11.46 | 11.38 | 11.01 |

*Table-3(g) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) 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%.*

| Cascaded VCRS | System:54 | System55 | System:56 | System57 | System58 | System59 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in LTC | *R452A* | *R452A* | *R452A* | *R452A* | *R452A* | *R452A* |
| HFC +HFO Blends in LTC | R513A | R454B | R454C | R448A | R449a | R452B |
| First Law Cascaded Efficiency COP_ $_{Cascade}$ | 0.6293 | 0.6122 | 0.5775 | 0.5829 | 0.5850 | 0.6219 |
| Cascade Exergy Destruction Ratio(EDR_ $_{Cascade}$) | 2.398 | 2.493 | 2.703 | 2.668 | 2.655 | 2.438 |
| Cascaded Exergetic Efficiency | 0.2936 | 0.2863 | 0.270 | 0.2726 | 0.2736 | 0.2908 |
| Exergy of Fuel "kW" | 56.01 | 57.44 | 60.90 | 60.33 | 60.11 | 56.55 |
| Exergy of Product "kW" | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.6919 | 0.7028 | 0.7290 | 0.7247 | 0.7230 | 0.6960 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.1353 | 0.2023 | 0.1888 | 0.1885 | 0.1359 |
| W_$_{comp_HTC}$"kW" | 42.79 | 43.46 | 45.08 | 44.81 | 44.71 | 43.04 |
| W_$_{comp_LTC}$ "kW" | 13.22 | 13.98 | 15.82 | 15.51 | 15.40 | 13.51 |
| Q_$_{Cond_HTC}$ "kW" | 91.18 | 92.61 | 96.07 | 95.50 | 95.28 | 91.71 |
| Q_$_{Cond_LTC}$ "kW" | 48.39 | 49.15 | 50.98 | 50.68 | 50.57 | 48.67 |
| Q_$_{Eva_HTC}$ "kW" | 48.39 | 49.15 | 50.98 | 50.68 | 50.57 | 48.67 |
| Q_$_{Eva_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.660 | 2.515 | 2.223 | 2.257 | 2.284 | 2.604 |
| First Law HTC Efficiency COP_ $_{HTC}$ | 1.131 | 1.131 | 1.131 | 1.131 | 1.131 | 1.131 |
| HTCExergy Destruction Ratio(EDR_$_{HTC}$) | 2.909 | 2.909 | 2.909 | 2.909 | 2.909 | 2.909 |
| HTC Exergetic Efficiency | 0.2558 | 0.2558 | 0.2558 | 0.2558 | 0.2558 | 0.2558 |
| HTC Exergy of Fuel "kW" | 42.79 | 43.46 | 45.08 | 44.81 | 44.71 | 43.04 |
| HTC Exergy of Product "kW" | 10.95 | 11.12 | 11.53 | 11.46 | 11.44 | 11.01 |

System-60: Cascaded vapour 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_$_{cond}$=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%.

System-61: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R454B low GWP 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_$_{Eva_LTC}$=-7o°C, Temperature overlapping=10, Compressor efficiency_$_{HTC}$=80%. Compressor efficiency_$_{LTC}$=80%.

System-62: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R454C low GWP 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%.

Table-63: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R448A low GWP 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%.

System-64: Cascaded vapour compression refrigeration system using ecofriendly low GWP 452B refrigerants in higher temperature cycle using ecofriendly R449A low GWP 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%.

System-65: Cascaded vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R452A low GWP 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%.

Table-3(h) shows the comparison of first law efficiency (COP_$_{Cascade}$) of cascaded vapour compression refrigeration systems using R452B in high temperature cycle and HFC +HFO Blends in low temperature cycle and it was found that cascaded vapour compression refrigeration systems using R452B in high temperature cycle and R513A in low temperature cycle (system-60) gives higher first law efficiency and exergetic efficiency lower exergy destruction ratio and cascaded vapour compression refrigeration systems using R452B in high temperature cycle and R452A in low temperature cycle (system-62) gives lower first law efficiency (COP_$_{Cascade}$) and exergetic efficiency and higher EDR.

*Table-3(h) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) 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%.*

| Cascaded VCRS | System:60 | System61 | System:62 | System63 | System64 | System65 |
|---|---|---|---|---|---|---|
| HFC +HFO Blends in LTC | *R452B* | *R452B* | *R452B* | *R452B* | *R452B* | *R452B* |
| HFC +HFO Blends in LTC | R513A | R454B | R454C | R448a | R449a | R452A |
| First Law Cascaded Efficiency $COP\__{Cascade}$ | 0.7603 | 0.7399 | 0.6948 | 0.7018 | 0.7045 | 0.7109 |
| Cascade Exergy Destruction Ratio($EDR\__{Cascade}$) | 1.812 | 1.890 | 2.078 | 2.049 | 2.035 | 2.008 |
| Cascaded Exergetic Efficiency | 0.3556 | 0.3460 | 0.3249 | 0.3282 | 0.3295 | 0.3324 |
| Exergy of Fuel “kW” | 46.25 | 47.53 | 50.62 | 50.11 | 49.92 | 49.47 |
| Exergy of Product “kW” | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.3010 | 0.3057 | 0.3171 | 0.3153 | 0.3146 | 0.3129 |
| LTC Mass flow Rate (Kg/sec) | 0.2245 | 0.1353 | 48.39 | 49.19 | 50.98 | 0.2461 |
| $W\_{comp\_HTC}$“kW” | 33.03 | 33.55 | 34.80 | 34.59 | 34.51 | 34.33 |
| $W\_{comp\_LTC}$ “kW” | 13.22 | 13.98 | 15.82 | 15.51 | 15.40 | 15.14 |
| $Q\_{Cond\_HTC}$ “kW” | 81.42 | 82.70 | 85.78 | 85.27 | 85.08 | 84.64 |
| $Q\_{Cond\_LTC}$ “kW” | 48.39 | 49.19 | 50.98 | 50.68 | 50.57 | 50.30 |
| $Q\_{Eva\_HTC}$ “kW” | 48.39 | 49.19 | 50.98 | 50.68 | 50.57 | 50.30 |
| $Q\_{Eva\_LTC}$ “kW” | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.660 | 2.515 | 2.223 | 2.267 | 2.284 | 2.3231 |
| First Law HTC Efficiency $COP\__{HTC}$ | 1.465 | 1.465 | 1.465 | 1.465 | 1.465 | 1.465 |
| HTCExergy Destruction Ratio($EDR\_{HTC}$) | 2.017 | 2.017 | 2.017 | 2.017 | 2.017 | 2.017 |
| HTC Exergetic Efficiency | 0.3314 | 0.3314 | 0.3314 | 0.3314 | 0.3314 | 0.3314 |
| HTC Exergy of Fuel “kW” | 33.03 | 33.55 | 34.80 | 34.59 | 34.51 | 34.33 |
| HTC Exergy of Product “kW” | 10.95 | 11.12 | 11.53 | 11.46 | 11.44 | 11.38 |

### *3.1 Computational optimal thermodynamic Performances of cascaded vapour compression refrigeration system using ecofriendly low GWP HFC+HFO blends (refrigerants) in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) in low temperature cycle*

Table-4(a) and Table-4(b) show the Optimum thermodynamic (energy-exergy) performances of cascaded vapour compression refrigeration system using ecofriendly low GWP HFC+HFO blends refrigerants in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) in low temperature cycle was obtained and it was found that cascaded vapour 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 highest (optimum) thermodynamic first law energy performance (COP) and second law (exergetic efficiency) performances. However lowest thermodynamic performances of cascaded vapour compression refrigeration system-14 using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle .

*Table-4(a) Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) 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%.*

| Optimal Cascaded VCRS | System: 17 | System 29 | System 30 | System: 36 | System 42 | System 48 | System 54 | System: 60 |
|---|---|---|---|---|---|---|---|---|
| HFC +HFO Blends in LTC | 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 | 0.7603 |
| 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” | 22.08 | 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" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| 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 |

*Table-4(b) Optimum (Minimum) thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R454C refrigerants in higher temperature cycle using ecofriendly low GWP HFC+HFO blends (refrigerants) 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%.*

| Optimal Cascaded VCRS | System 19 | System 25 | System 31 | System: 38 | System 44 | System 50 | System 56 | System: 62 |
|---|---|---|---|---|---|---|---|---|
| HFC +HFO Blends in LTC | R450A | R513A | R454B | R454C | R448A | R449A | R452A | R452B |
| HFC +HFO Blends in LTC | R454C | R448a | R454C | R448a | R454C | R454C | R448a | R454C |
| First Law Cascaded Efficiency $COP_{Cascade}$ | 0.6791 | 0.6735 | 0.6845 | 0.6217 | 0.6550 | 0.6550 | 0.5829 | 0.6948 |
| Exergy Destruction Ratio($EDR_{Cascade}$) | 2.149 | 2.175 | 2.124 | 2.439 | 2.265 | 2.265 | 2.668 | 2.078 |
| Cascaded Exergetic Efficiency | 0.3176 | 0.3149 | 0.3201 | 0.2937 | 0.3063 | 0.3063 | 0.2726 | 0.3249 |
| Exergy of Fuel "kW" | 51.79 | 52.22 | 51.38 | 56.53 | 53.69 | 53.69 | 60.33 | 50.62 |
| Exergy of Product "kW" | 22.08 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 | 16.45 |
| HTC Mass flow Rate (Kg/sec) | 0.5338 | 0.5886 | 0.3198 | 0.5215 | 0.4552 | 0.4552 | 0.7247 | 0.3171 |
| LTC Mass flow Rate (Kg/sec) | 0.2023 | 0.1888 | 0.2023 | 0.1888 | 0.2023 | 0.2023 | 0.1888 | 48.39 |
| $W_{comp\_HTC}$"kW" | 35.97 | 36.70 | 35.56 | 41.05 | 37.87 | 37.87 | 44.81 | 34.80 |
| $W_{comp\_LTC}$ "kW" | 15.82 | 15.51 | 15.82 | 15.51 | 15.82 | 15.82 | 15.51 | 15.82 |
| $Q_{Cond\_HTC}$ "kW" | 86.95 | 87.39 | 86.54 | 91.73 | 88.86 | 88.86 | 95.50 | 85.78 |
| $Q_{Cond\_LTC}$ "kW" | 50.98 | 50.68 | 50.98 | 50.68 | 50.98 | 50.98 | 50.68 | 50.98 |
| $Q_{Eva\_HTC}$ "kW" | 50.98 | 50.68 | 50.98 | 50.68 | 50.98 | 50.98 | 50.68 | 50.98 |
| $Q_{Eva\_LTC}$ "kW" | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| First Law LTC Efficiency COP_LTC | 2.223 | 2.267 | 2.223 | 2.267 | 2.223 | 2.223 | 2.257 | 2.223 |
| First Law HTC Efficiency $COP_{HTC}$ | 1.417 | 1.381 | 1.434 | 1.235 | 1.346 | 1.346 | 1.131 | 1.465 |
| HTC Exergy Destruction Ratio($EDR_{HTC}$) | 2.199 | 2.202 | 2.083 | 2.581 | 2.284 | 2.284 | 2.909 | 2.017 |
| HTC Exergetic Efficiency | 0.3206 | 0.3123 | 0.3243 | 0.2793 | 0.3045 | 0.3045 | 0.2558 | 0.3314 |
| HTC Exergy of Fuel "kW" | 36.97 | 36.70 | 35.56 | 41.05 | 37.87 | 37.87 | 44.81 | 34.80 |
| HTC Exergy of Product "kW" | 11.53 | 11.46 | 11.53 | 11.45 | 11.53 | 11.53 | 11.46 | 11.53 |

## 4. Conclusions

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

(i) Optimal Cascaded vapour compression refrigeration system using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle (system-60) gives best (optimum) thermodynamic first law energy performance (COP) and second law (exergetic efficiency) performances.

(ii) Second cascaded vapour compression refrigeration system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly R513a low GWP refrigerant in low temperature cycle (system-17) gives slightly less thermodynamic performances. than system-4 using ecofriendly low GWP R452B refrigerants in higher temperature cycle using ecofriendly R513A low GWP refrigerant in low temperature cycle

(iii) The lowest thermodynamic performances were observed by using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle in the Cascaded thermodynamic performances of vapour compression refrigeration (system-41)

(iv) Cascaded vapour compression refrigeration system using R454B in high temperature cycle and R513A in low temperature cycle (system13) at -90°C gives higher first law efficiency and exergetic efficiency and lower exergy destruction ratio.

(v) Cascaded vapour compression refrigeration system-14 using R452A in high temperature cycle and R449A in low temperature cycle (system-12) at -90°C gives lower first law efficiency ($COP_{Cascade}$) and exergetic efficiency and higher exergy destruction ratio.

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