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**ORIGINAL ARTICLE**

# Thermodynamic performances of cascaded vapour compression refrigeration systems using HFO refrigerants for ultra-low temperature applications

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## Abstract

This work compares the thermodynamic performances of ultra-low GWP eight HFO refrigerants using mathematical modeling with the input design parameters of evaporator and condenser temperatures variations and variations in temperature overlapping between cascade condenser and cascade evaporator, and computed compressors work input, the coefficient of performance (COP), exergy destruction Ratio and exergetic efficiency, of HFO refrigerants which were examined for comparative performance analysis with R134a taken as the baseline refrigerant. The effect of temperature overlapping in cascaded condenser and subcooling of high temperature condenser was studied in detail. It's found that cascaded (energy&exergy) performances improved by increasing sub cooling in the condenser. The temperature overlapping was also observed and found that when overlapping temperature increases, thermodynamic (Energy-exergy) performances are decreases. Therefore, this research will help in finding alternative HFO refrigerants for the next generation of refrigeration systems that have environmentally friendly characteristics compared to previously used refrigerants for a sustainable environment. 

## 1. Introduction

Global warming is one of most cruel environmental concerns that our planet is facing today. One of its causes is the previous generation of refrigerant gases and carbon dioxide emissions. Upon release, these gases remain in the atmosphere for longer periods and contribute towards global warming. The severity of these gases' environment impacts is determined by their life cycle analysis (LCA) and the conversion efficiency of refrigeration systems. Due to global warming, Earth's temperature is expected rise over the period of the next 100 years. This will affect agriculture, which will cause in heavy rainfalls, additional heat waves, and sea level can rise of by the next century. Therefore, the member countries of the Montreal Protocol in 2016, agreed to phase down hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) to reduce net earth warming by 0.5 °C by the year 2100 and to protect the ozone layer. Chlorofluorocarbons (CFCs) and HCFCs were already depleting the ozone layer, so these were wiped out after the Montreal Protocol and the Kyoto Protocol, respectively [1-4]. Presently, the different refrigerants being used for domestic, automotive, commercial refrigeration and air-conditioning systems are mostly HFCs, i.e., R134a, R23, R404A, R407A, R410A, R125 and R507A. Though HFCs have zero ozone depletion potential (ODP), these still possess large global warming potential (GWP) values. R134a has a GWP of 1430, R23 has a GWP of 14800, R404A has a GWP of 3922, R410A has a GWP of 2088, R407A has a GWP of 2107, and R507A has

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a GWP of 3985 [5]. The HCFC refrigerant (R22) was being used in the earlier generation of commercial refrigeration systems, e.g., centrifugal chillers and central air conditioning systems that are used in buildings, and the current generation is using R134a and R123. As per the safety classifications of refrigerants, R22 comes under the category of A1: very low toxicity and no flame propagation, but it has large GWP of 1810. R134a is a globally accepted refrigerant for various types of refrigeration systems. It has a superior safety rating compared with A1, and it has a low toxicity, no flame propagation, and a GWP around 1430. It is also an HFC and will be phased down 100% by 2034. R123 is used in chillers due to its high thermodynamic efficiency and reduced possibility of leakages, but it is HCFC compound with a B1 classification, and it has been a cause of tumors in livers and pancreases due to long term inhalation and hence, it is expected to be phased out by 2025. Due to the large GWP values of the earlier generation of refrigerants, the USA's Environmental Protection Agency (EPA) has decided to systematically phase out HFCs to 50% by 2025, 80% by 2030, and 100% by 2040 [6-11].

Therefore, it is necessary to find substitute refrigerant for the sustainability of the environment that should have a low GWP for minimum environmental impact and was found that as a drop-in replacement of R134a on vapor compression refrigeration (VCRC) with a variable speed compressor and input parameters of evaporator and condenser temperature. As compared to R404a, the HFC-134a gives 3% to 5% higher first law efficiency(COP). Similarly, R410a and R407c also have1% to 1.5% lower first law efficiency than using R134a [12-16]. The results showed that with the R1234yf decreased to 5 to 10% the first law (energy) efficiency (COP) and by using R1234ze(Z) the energy efficiency (COP) was increased from 3 to 7%. The thermodynamic performances of vapour compression refrigeration systems using R152a are 2 to 6% higher than using R134a. It was observed that the input power of R152a was 7.724%, 7.72% and 7.752% less than that of R134a, the COP of system using R1224yd(Z) a showed a 2.35%, 3.15% and 4.95% improvement at compressor speeds of 2000, 2500 and 3000 rpms, respectively, as compared to R134a [17-20].

The HFO-1234yf and HFO-1234ze(E) and R1234ze(Z), R1243zf, R1224yd(Z), R1225ye(Z), R1233zd(E), HFO-1336mzz(Z) were analyzed as potential replacements for R134a and the results showed that R1234ze(E) and R1243zf showed the closest performance to R134a. compared to R1234ze(E) [21-26]. The suitability of eight HFO refrigerants such as HFO-1234yf and HFO-1234ze(E), as potential alternatives to R134a was studied by using the EES software, which showed that these refrigerants improved performance without significantly increasing the GWP [27-30]. The use of R1233zd(E)', R1224yd(Z) and R1234ze(Z) in terms of first law efficiency to be 0.9%, was better than R245fa

The first law (energy) performance in terms of coefficient of performance (CO) and second law (exergy) performance of ultra-low GWP refrigerants as drop-in replacements was evaluated by varying the value of the evaporating and condensing temperatures of a VCRC-based refrigeration system have been studied in details in simple vapour compression refrigeration systems, cascaded refrigeration systems for ultra-low temperature applications.

## 2. Results and Discussion

### *2.1 Performances of vapour compression refrigeration systems using HFO refrigerants*

Thermodynamic first law (Energy) performance (i.e. coefficient of performance) of HFO ecofriendly refrigerants using heat exchanger for condenser temperature of 50ºC and *-10ºC,* evaporator temperature for 3.5167 kW cooling capacity shown in table-1(a) respectively It was found that the HFO-1234ze(Z) refrigerant gives highest COP. Similarly, HFO R1224yd(Z) refrigerant can be used to evaporator temperature above -10ºC. the second best ultra-low refrigerant is R1233zd(E) gives slightly low thermodynamic energy-exergy performances than R1234ze(Z). Although first law energy performance (COP) using HFO-1336mzz(Z) gives nearly same COP as compared to R1224yd(Z). The thermodynamic energy performance using R1243zf is nearly similar as compared to performance R1234ze(E). The thermodynamic energy performance (COP) of R1234ze(Z), R1224yd(Z), R-1233zd(E) and HFO-1336mzz(Z) is higher than HFC-134a. Although energy performance (COP) of R1234ze(E), R1243zf and R1225ye(Z) is slightly lower than HFC-134a. HFO-1234yf gives lowest thermodynamic energy performance(COP). Similarly work required to run compressor using R 1234yf is highest which consumed high electrical energy. While R1234ze(Z) required lower electrical power consumption. It was found that R1234ze(Z), R1234ze(Z) and R1243zf can be only used -30ºC above evaporator temperature which can replace HFC refrigerants in coming future. Although R1234yf has low thermodynamic energy performance as compared to HFC-134a, which can be used evaporator temperature above -50ºC. The second law (exergy) performance using R1234ze(Z) is highest. The second law (exergetic) efficiency using R1233zd(E) is slightly lower than R1234ze(Z) but higher than HFO-1336mzz(Z). Similarly, exergetic efficiency using R1224yd(Z) is higher than R134a while using R1234yf gives lowest second law (exergetic) performance. Similarly, exergy destruction ratio is highest. The exergy destruction in the various components of vapour compression system are shown in Table-1(b) respectively. It was found that maximum exergy destruction occurred the condenser which can be reduced by changing proper design of condensing heat exchanger. It was found that by using R1234yf, the mass flow rate of refrigerant in the system is increased.

*Table-1(a) Effect of ecofriendly refrigerants system performances of simple vapour compression refrigeration systems for (T_Cond =50°C, and T_Evap = -10°C, isentropic compressors efficiency =80%.*

| Ecofriendly Refrigerants | First law Efficiency ($COP_{VCRS}$ | Exergy Destruction Ratio ($EDR_{system}$ ) | VCRS Exergetic Efficiency | Work required to run Compressor $W_{Comp}$"kW" | Mass flow rate of refrigerant in VCRS(kg/sec) | Exergy Destruction Ratio ($EDR_{VCRS}$ ) | VCRS Second law Efficiency |
|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.851 | 1.563 | 0.3902 | 1.234 | 0.02248 | 1.628 | 0.3806 |
| R1234ze(E) | 2.589 | 1.645 | 0.3543 | 1.359 | 0.03081 | 1.905 | 0.3443 |
| R1224yd(Z) | 2.762 | 1.822 | 0.3780 | 1.273 | 0.02982 | 1.710 | 0.3690 |
| R1243zf | 2.589 | 1.593 | 0.3543 | 1.359 | 0.02766 | 1.888 | 0.3463 |
| R1233zd(E) | 2.818 | 1.863 | 0.3857 | 1.248 | 0.02482 | 1.657 | 0.3763 |
| R1225ye(Z) | 2.417 | 1.788 | 0.3493 | 1.378 | 0.03633 | 1.928 | 0.3415 |
| HFO-1336mzz(Z) | 2.715 | 1.69 | 0.3717 | 1.295 | 0.02986 | 1.756 | 0.3629 |
| R1234yf | 2.252 | 2.023 | 0.3308 | 1.455 | 0.03726 | 2.088 | 0.3239 |
| R134a | 2.621 | 1.788 | 0.3587 | 1.342 | 0.02732 | 1.854 | 0.3504 |

*Table-1(b) Effect of ecofriendly refrigerants system performances of vapour compression refrigeration systems for (T_Cond =50°C, and T_Evap = -10°C, isentropic compressors efficiency =80%.*

| Ecofriendly Refrigerants | First law Efficiency ($COP_{VCRS}$) | Exergy Destruction Ratio ($EDR_{VCRS}$ ) | % Exergy Destruction in comp. | % Exergy Destruction in cond. | % Exergy Destruction in valve. | Second law (exergetic) Efficiency | Mass flow rate of refrigerants in VCRS | Work required to run Compressor $W_{CompHTC}$"kW" |
|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.851 | 1.563 | 17.92 | 30.53 | 13.8 | 0.3902 | 0.02248 | 1.234 |
| R1234ze(E) | 2.589 | 1.645 | 18.37 | 28.37 | 19.54 | 0.3543 | 0.03081 | 1.359 |
| R1224yd(Z) | 2.762 | 1.822 | 18.39 | 29.3 | 15.73 | 0.3780 | 0.02982 | 1.273 |
| R1243zf | 2.589 | 1.593 | 18.15 | 28.37 | 19.2 | 0.3543 | 0.02766 | 1.359 |
| R1233zd(E) | 2.818 | 1.863 | 18.24 | 29.88 | 14.56 | 0.3857 | 0.02482 | 1.248 |
| R1225ye(Z) | 2.252 | 1.788 | 18.33 | 27.89 | 19.99 | 0.3493 | 0.03633 | 1.378 |
| HFO1336mzz(Z) | 2.715 | 1.69 | 18.44 | 28.85 | 16.74 | 0.3717 | 0.02986 | 1.295 |
| R1234yf | 2.417 | 2.023 | 18.40 | 26.85 | 22.74 | 0.3308 | 0.03726 | 1.455 |
| R134a | 2.621 | 1.788 | 17.82 | 29.15 | 18.34 | 0.3587 | 0.02732 | 1.342 |

Thermodynamic first law (Energy) performance (i.e. coefficient of performance) of HFO ecofriendly refrigerants using heat exchanger for condenser temperature of 50°C and *-30°C,* evaporator temperature for 3.5167 kW cooling capacity shown in table-2(a) respectively It was found that the HFO-1234ze(Z) refrigerant gives highest COP. The second best ultra-low refrigerant is R1233zd(E) gives slightly low thermodynamic energy-exergy performances than R1234ze(Z). Although first law energy performance (COP) using HFO-1336mzz(Z) gives higher COP as compared to R1225ye(Z). The thermodynamic energy performance using R1243zf is nearly similar as compared to performance R1234ze(E). The thermodynamic energy performance (COP) of R1234ze(Z), R-1233zd(E) and HFO-1336mzz(Z) is higher than HFC-134a. Although energy performance (COP) of R1234ze(E), R1243zf and R1225ye(Z) is slightly lower than HFC-134a. HFO-1234yf gives lowest thermodynamic energy performance(COP). Similarly work required to run compressor using R 1234yf is highest which consumed high electrical energy. While R1234ze(Z) required lower electrical power consumption. It was found that R1234ze(Z), R1234ze(Z) and R1243zf can be only used -30°C above evaporator temperature which can replace HFC refrigerants in coming future. Although R1234yf has low thermodynamic energy performance as compared to HFC-134a , which can be used evaporator temperature above -50°C.

The second law (exergy) performance using R1234ze(Z) is highest. The second law (exergetic) efficiency using R1233zd(E) is slightly lower than R1234ze(Z) but higher than HFO-1336mzz(Z). Similarly, exergetic efficiency using R1233zd(E) is higher than R134a while using R1234yf gives lowest second law (exergetic) performance. Similarly, exergy destruction ratio is highest. The exergy destruction in the various components of vapour compression system are shown in Table-2(b) respectively. It was found that maximum exergy destruction occurred the condenser which can be reduced by changing proper design of condensing heat exchanger. It was found that by using R1234yf , the mass flow rate of refrigerant in the system is increased.

*Table-2(a) Effect of refrigerants system performances of VCRS for (T_Cond =50ºC, and T_Evap = -30ºC, isentropic compressors efficiency =80%.*

| Ecofriendly Refrigerants | First law Efficiency (COP_ VCRS | ($EDR_{system}$) | VCRS Exergetic Eff | Work required to run Compressor $W_{CompHTC}$"kW | Mass flow rate of refrigerants in VCRS (kg/sec) | ($EDR\_{VCRS}$ ) | VCRS Second law Eff | Work required to run Comp $W_{CompHTC}$"kW" |
|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 1.757 | 1.414 | 0.4142 | 1.957 | 0.02462 | 1.457 | 0.4071 | 1.957 |
| R1234ze(E) | 1.564 | 1.775 | 0.3604 | 2.249 | 0.03518 | 1.833 | 0.3530 | 2.249 |
| R1243zf | 1.585 | 1.738 | 0.3653 | 2.219 | 0.03098 | 1.780 | 0.3597 | 2.219 |
| R1233zd(E) | 1.757 | 1.470 | 0.4049 | 2.002 | 0.0276 | 1.512 | 0.3981 | 2.022 |
| R1225ye(Z) | 1.546 | 1.806 | 0.3564 | 2.274 | 0.04125 | 1.848 | 0.3511 | 2.274 |
| HFO-1336mzz(Z) | 1.650 | 1.630 | 0.3802 | 2.132 | 0.03424 | 1.673 | 0.3741 | 2.132 |
| R1234yf | 1.429 | 2.037 | 0.3293 | 2.461 | 0.04339 | 2.088 | 0.3248 | 2.461 |

*Table-2(b) Effect of refrigerants system performances of VCRS for (T_Cond =50ºC, and T_Evap = -30ºC, isentropic compressors efficiency =80%.*

| Ecofriendly Refrigerants | First law Efficiency (COP_ VCRS | Exergy Destruction Ratio ($EDR_{VCRS}$ ) | % Exergy Destruction in comp. | % Exergy Destruction in cond. | % Exergy Destruction in valve | Second law Efficiency | Mass flow rate of refrigerants in VCRS | Work required to run Compressor $W_{CompHTC}$"kW" |
|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 1.757 | 1.414 | 17.47 | 22.92 | 19.07 | 0.4071 | 0.02462 | 1.957 |
| R1234ze(E) | 1.564 | 1.775 | 18.22 | 20.26 | 26.53 | 0.3530 | 0.03518 | 2.249 |
| R1243zf | 1.585 | 1.738 | 17.87 | 20.85 | 25.53 | 0.3597 | 0.03098 | 2.219 |
| R1233zd(E) | 1.757 | 1.470 | 17.9 | 21.98 | 20.49 | 0.3981 | 0.0276 | 2.002 |
| R1225ye(Z) | 1.546 | 1.806 | 18.13 | 20.22 | 26.76 | 0.3511 | 0.04125 | 2.274 |
| HFO1336mzz(Z) | 1.65 | 1.630 | 18.44 | 20.58 | 23.77 | 0.3741 | 0.03424 | 2.132 |
| R1234yf | 1.429 | 2.037 | 18.31 | 19.81 | 30.27 | 0.3248 | 0.04339 | 2.461 |

### *2.2 Performances of two cascaded vapour compression refrigeration system using HFO refrigerants*

The following input data have been used for computing thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly ultra-low GWP refrigerants in lower temperature cycle and high temperature cycles.

| S.No | Input Data | Numerical value |
|---|---|---|
| 1 | Condenser temperature in the high temperature cycle | 55ºC |
| 2 | Sub cooling | 0,5,10,15,20,25 |
| 3 | Temperature overlapping | 0,5,10,15,20 |
| 4 | Cooling load on low temperature evaporator (kW) | 35.167 |
| 5 | Isentropic efficiency of high temperature compressor | 80% |
| 6 | Isentropic efficiency of lowtemperature compressor | 80% |
| 7 | HFO refrigerants used in low temperature cycle (LTC) | R1233zd(E), HFO-1336mzz(Z) and R1225ye(Z) |

The performance of cascade vapour compression refrigeration system is shown in table-3(a) to 3(b) respectively.

Table-3(a) and Table-3(b) **,** show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap\_{LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T\_{Evap\_HTC}$) at -30ºC,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature.

Table-4(a) and Table-4(b) **,** show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap\_{LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T\_{Evap\_HTC}$) at -10ºC,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80% , Cooling load =35.167 kW, temperature overlapping=10ºC) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature. Table-5(a) to Table-5(c) **,** show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap\_{LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T\_{Evap\_HTC}$) at

10ºC,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80% , Cooling load =35.167 kW, temperature overlapping=10ºC) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature.

*Table-3(a) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R-1225ye(Z) in low temperature cycle evaporator ($T_{\_Evap\_LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -30ºC, ($T_{\_Cond}$ =50ºC), and subcooling of condenser at 45ºC and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | First law Efficiency ($COP_{HTC}$) | HTC Exergetic Efficiency | HTC EDR | Cascade COP | Cascade Exergetic Efficiency | Cascade EDR | First law Efficiency ($COP_{\_LTC}$ ) | Cascade COP | Second law Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 1.634 | 2.119 | 0.3764 | 0.5645 | 0.3838 | 1.606 | 1.391 | 0.6944 | 0.3207 |
| R1234ze(E) | 1.386 | 2.642 | 0.3193 | 0.5103 | 0.3469 | 1.883 | 1.391 | 0.6584 | 0.2747 |
| R1243zf | 1.408 | 2.572 | 0.3244 | 0.5154 | 0.3503 | 1.854 | 1.391 | 0.6619 | 0.2799 |
| R1233zd(E) | 1.593 | 2.192 | 0.3672 | 0.5562 | 0.3781 | 1.645 | 1.391 | 0.6891 | 0.3133 |
| HFO1336mzz(Z) | 1.481 | 2.414 | 0.3412 | 0.5319 | 0.3616 | 1.766 | 1.391 | 0.6731 | 0.2929 |
| R1234yf | 1.242 | 3.009 | 0.2863 | 0.4755 | 0.3232 | 2.094 | 1.391 | 0.6334 | 0.2494 |

*Table-3(b) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using HFO-1336mzz(Z) in low temperature cycle evaporator ($T\_Evap_{\_LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -30ºC, ($T_{\_Cond}$=50ºC), and isentropic HTC&LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | First law Efficiency ($COP_{\_HTC}$) | HTC Exergetic Efficiency | HTC EDR | Cascade COP | Cascade Exergetic Efficiency | Cascade EDR | First law Efficiency ($COP_{\_LTC}$ ) | Cascad e COP | Second law Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 1.634 | 0.3764 | 2.119 | 0.5542 | 0.6884 | 1.654 | 1.352 | 0.6884 | 0.3207 |
| R1234ze(E) | 1.386 | 0.3193 | 2.62 | 0.5013 | 0.6520 | 1.935 | 1.352 | 0.6520 | 0.2746 |
| R1243zf | 1.408 | 0.3244 | 2.572 | 0.5062 | 0.6556 | 1.906 | 1.352 | 0.6556 | 0.2799 |
| R1233zd(E) | 1.593 | 0.2973 | 2.192 | 0.5461 | 0.6830 | 1.694 | 1.352 | 0.6830 | 0.3133 |
| R1225ye(Z) | 1.366 | 0.3148 | 2.673 | 0.4968 | 0.6488 | 1.951 | 1.352 | 0.6488 | 0.2723 |
| R1234yf | 1.242 | 0.2863 | 3.009 | 0.4673 | 0.6268 | 2.148 | 1.352 | 0.6268 | 0.2494 |
| R134a | 1.441 | 0.3320 | 2.494 | 0.5136 | 0..6608 | 1.864 | 1.352 | 0.6608 | 0.2862 |

*Table-4(a) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R-1225ye(Z) in low temperature cycle evaporator ($T\_Evap_{\_LTC}$) at = -95ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -30ºC, ($T_{\_Cond}$ =50ºC) and subcooling of condenser at 45ºC and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First Law Efficiency ($COP_{HTC}$) | HTC EDR | LTC First law Efficiency | Second law Efficiency | Cascade COP | Cascade Exergetic Efficiency | Cascade Exergy Destruction Ratio | HTC mc(t) | LTC mc(t) |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 1.713 | 1.534 | 1.352 | 0.3947 | 0.6984 | 0.3873 | 1.582 | 0.4495 | 0.2534 |
| R1234ze(E) | 1.448 | 1.997 | 1.352 | 0.3336 | 0.6619 | 0.3502 | 1.856 | 0.6611 | 0.2534 |
| R1243zf | 1.472 | 1.941 | 1.352 | 0.3392 | 0.6656 | 0.3538 | 1.827 | 0.5802 | 0.2534 |
| R-1225ye(Z) | 1.669 | 2.041 | 1.352 | 0.3289 | 0.6587 | 0.3471 | 1.881 | 0.7775 | 0.2534 |
| R1233zd(E) | 1.427 | 1.60 | 1.352 | 0.3847 | 0.693 | 0.3815 | 1.621 | 0.5052 | 0.2534 |
| R1234yf | 1.295 | 2.350 | 1.352 | 0.2985 | 0.6366 | 0.3265 | 2.063 | 0.8325 | 0.2534 |
| R134a | 1.508 | 1.878 | 1.352 | 0.3475 | 0.6709 | 0.3591 | 1.785 | 0.5628 | 0.2534 |

*Table-4(b) Effect of refrigerants on the system performances of cascaded VCRS using HFO-1336mzz(Z) in low temperature cycle evaporator at -95ºC and following ultra-low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -30ºC, ($T_{\_Cond}$=50ºC), and subcooling of condenser at 45ºC and isentropic HTC&LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First Law Efficiency ($COP_{HTC}$) | HTC EDR | LTC First law Efficiency | Second law Efficiency | Cascade COP | Cascade Exergetic Efficiency | Cascad e EDR | HTC mc(t) | LTC mc(t) |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 1.713 | 1.534 | 1.391 | 0.3947 | 0.7043 | 0.3946 | 1.534 | 0.4442 | 0.2802 |
| R1234ze(E) | 1.448 | 1.997 | 1.391 | 0.3336 | 0.6681 | 0.3566 | 1.805 | 0.6533 | 0.2802 |
| R1243zf | 1.472 | 1.941 | 1.391 | 0.3392 | 0.6718 | 0.3602 | 1.776 | 0.5732 | 0.2802 |
| R1233zd(E) | 1.669 | 2.041 | 1.391 | 0.3847 | 0.6989 | 0.3887 | 1.573 | 0.4993 | 0.2802 |
| HFO1336mzz(Z) | 1.547 | 1.60 | 1.391 | 0.3565 | 0.6827 | 0.3714 | 1.692 | 0.6276 | 0.2802 |
| R1234yf | 1.295 | 2.350 | 1.391 | 0.2985 | 0.6431 | 0.3322 | 2.010 | 0.8227 | 0.2802 |
| R134a | 1.508 | 1.878 | 1.391 | 0.3475 | 0.6771 | 0.3656 | 1.735 | 0.5562 | 0.2802 |

*Table-5(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1233ze(E) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -75ºC and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -10ºC, ($T_{\_Cond}$ =50ºC), and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First Law Efficiency ($COP_{HTC}$) | HTC EDR | LTC First law Efficiency | Second law Efficiency | Cascade COP | Cascade Exergetic Efficiency | Cascade EDR | HTC mc(t) | LTC mc(t) |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.728 | 1.678 | 1.556 | 0.3735 | 0.8093 | 0.4098 | 1.440 | 0.3859 | 0.2309 |
| R1234ze(E) | 2.420 | 2.019 | 1.556 | 0.3313 | 0.7902 | 0.3860 | 1.591 | 0.5414 | 0.2309 |
| R1243zf | 2.424 | 2.014 | 1.556 | 0.3317 | 0.7904 | 0.3863 | 1.589 | 0.4852 | 0.2309 |
| R-1224yd(Z) | 2.622 | 1.786 | 1.556 | 0.3589 | 0.8032 | 0.4019 | 1.488 | 0.5159 | 0.2309 |
| R-1225ye(Z) | 2.378 | 2.072 | 1.556 | 0.3255 | 0.7872 | 0.3825 | 1.614 | 0.6403 | 0.2309 |
| HFO1336mzz(Z) | 2.568 | 1.845 | 1.556 | 0.3515 | 0.7998 | 0.3978 | 1.514 | 0.5185 | 0.2309 |
| R1234yf | 2.223 | 2.286 | 1.556 | 0.3043 | 0.7757 | 0.3692 | 1.709 | 0.6656 | 0.2309 |
| R134a | 2.464 | 1.964 | 1.556 | 0.3373 | 0.7932 | 0.3896 | 1.567 | 0.4773 | 0.2309 |

*Table-5(b) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -75ºC and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -10ºC, ($T_{\_Cond}$ =50ºC), and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First Law Efficiency ($COP_{HTC}$) | HTC EDR | LTC First law Efficiency | Second law Efficiency | Cascade COP | Cascade Exergetic Efficiency | Cascade EDR | HTC mc(t) | LTC mc(t) |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.728 | 1.678 | 1.516 | 0.3735 | 0.8059 | 0.4024 | 1.485 | 0.3899 | 0.3080 |
| R1234ze(E) | 2.420 | 2.019 | 1.516 | 0.3313 | 0.7859 | 0.3792 | 1.637 | 0.5469 | 0.3080 |
| R1243zf | 2.424 | 2.014 | 1.516 | 0.3317 | 0.7861 | 0.3795 | 1.635 | 0.4902 | 0.3080 |
| R1224yd(Z) | 2.622 | 1.786 | 1.516 | 0.3589 | 0.7991 | 0.3947 | 1.533 | 0.5211 | 0.3080 |
| R1233zd(E) | 2.691 | 1.715 | 1.516 | 0.3684 | 0.8032 | 0.3997 | 1.502 | 0.4312 | 0.3080 |
| HFO-1336mzz(Z) | 2.568 | 1.845 | 1.516 | 0.3515 | 0.7957 | 0.3907 | 1.560 | 0.5242 | 0.3080 |
| R1234yf | 2.223 | 2.286 | 1.516 | 0.3043 | 0.7712 | 0.3628 | 1.756 | 0.6724 | 0.3080 |
| R134a | 2.464 | 1.964 | 1.516 | 0.3373 | 0.7889 | 0.3827 | 1.613 | 0.4822 | 0.3080 |

*Table-5(c) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using HFO-1336mzz(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\_Evap\_HTC}$) at -10ºC, ($T_{\_Cond}$=50ºC), and isentropic HTC&LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First law Efficiency ($COP_{HTC}$) | HTC EDR | LTC First law Eff | Second law Efficiency | Cascade COP | Cascade EDR | Cascad e EDR | HTC mc(t) | LTC mc(t) |
|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.728 | 1.678 | 1.516 | 0.3735 | 0.8059 | 0.4024 | 1.485 | 0.3913 | 0.2765 |
| R1234ze(E) | 2.420 | 2.019 | 1.516 | 0.3313 | 0.7859 | 0.3792 | 1.637 | 0.549 | 0.2765 |
| R1243zf | 2.424 | 2.014 | 1.516 | 0.3317 | 0.7861 | 0.3795 | 1.635 | 0.4920 | 0.2765 |
| R1224yd(Z) | 2.622 | 1.786 | 1.516 | 0.3589 | 0.7991 | 0.3947 | 1.533 | 0.5231 | 0.2765 |
| R1233zd(E) | 2.691 | 1.715 | 1.516 | 0.3684 | 0.8032 | 0.3997 | 1.502 | 0.4328 | 0.2765 |
| R1225ye(Z) | 2.378 | 2.072 | 1.516 | 0.3255 | 0.7813 | 0.3734 | 1.678 | 0.6493 | 0.2765 |
| R1234yf | 2.223 | 2.286 | 1.516 | 0.3043 | 0.7712 | 0.3628 | 1.756 | 0.6749 | 0.2765 |
| R134a | 2.464 | 1.964 | 1.516 | 0.3373 | 0.7889 | 0.3827 | 1.613 | 0.4840 | 0.2765 |

Table-6(a-c) **,** show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -75ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T_{\_Evap\_HTC}$) at -30ºC,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature. Table-7(a-b) ,shows the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -95ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T_{\_Evap\_HTC}$) at -30ºC,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80% , Cooling load =35.167 kW, temperature overlapping=10ºC) it was found best thermodynamic performances using HFO-1336mzz(Z)in LTC and R1234ze(Z).

*Table-6(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1233yd(E) in low temperature cycle evaporator (T_Evap_LTC) at = -75ºC and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for T_Evap_HTC) at -20ºC, (T_Cond=55ºC), and subcooling of condenser at 50ºC, isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First Law Eff (COPHTC) | HTC EDR | HTC 2nd law (Exergetic) Efficiency | LTC 1st law Eff | HTC work kW | LTC work "kW" | Cascade 1st law eff Cascade COP_ Cas | Cascade Exergetic Eff | Cascade EDR | HTC Q_Cond "kW" | LTC Q_Cond = HTC Q_EVA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.029 | 1.771 | 0.3609 | 1.892 | 26.49 | 18.59 | 0.7801 | 1.538 | 0.3940 | 80.25 | 53.76 |
| R1234ze(E) | 1.767 | 2.183 | 0.3142 | 1.892 | 30.43 | 18.59 | 0.7174 | 1.760 | 0.3623 | 84.18 | 53.76 |
| R1243zf | 1.779 | 2.160 | 0.3165 | 1.892 | 30.21 | 18.59 | 0.7206 | 1.748 | 0.3639 | 83.97 | 53.76 |
| HFO1336mzz(Z) | 1.88 | 1.99 | 0.3343 | 1.892 | 28.59 | 18.59 | 0.7454 | 1.656 | 0.3765 | 82.34 | 53.76 |
| R-1225ye(Z) | 1.738 | 2.235 | 0.3091 | 1.892 | 30.93 | 18.59 | 0.7102 | 1.788 | 0.3587 | 84.69 | 53.76 |
| R1234yf | 1.606 | 2.501 | 0.2856 | 1.892 | 33.47 | 18.59 | 0.6755 | 1.931 | 0.3411 | 87.23 | 53.76 |
| R134a | 1.841 | 2.099 | 0.3227 | 1.892 | 29.63 | 18.59 | 0.7293 | 1.715 | 0.3683 | 83.39 | 53.76 |
| R245fa | 1.944 | 1.892 | 0.3458 | 1.892 | 27.65 | 18.59 | 0.7605 | 1.604 | 0.3841 | 81.43 | 53.76 |

*Table-6(b) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using HFO-1336mzz(Z) in low temperature cycle evaporator (T_Evap_LTC) at = -95ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_Evap_HTC) at -20ºC, (T_Cond =55ºC), and sub cooling at 50ºC) isentropic HTC&LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC First Law Eff (COPHTC) | HTC EDR | HTC 2nd law (Exergetic) Efficiency | LTC 1st law Eff | HTC work kW | LTC work kW | Cascade 1st law eff Cascade COP_ Cas | Cascade Exergetic Eff | Cascade EDR | HTC Q_Cond "kW" | LTC Q_Cond= Q_EVA_HTC "kW" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.029 | 1.771 | 0.3609 | 1.845 | 26.72 | 19.06 | 0.7681 | 1.578 | 0.3879 | 80.95 | 54.23 |
| R1234ze(E) | 1.767 | 2.183 | 0.3142 | 1.845 | 30.70 | 19.06 | 0.7068 | 1.801 | 0.3570 | 83.97 | 54.23 |
| R1243zf | 1.779 | 2.160 | 0.3165 | 1.845 | 30.48 | 19.06 | 0.7099 | 1.789 | 0.3585 | 84.70 | 54.23 |
| R1233zd(E) | 1.88 | 1.822 | 0.3543 | 1.845 | 27.22 | 19.06 | 0.7599 | 1.608 | 0.3838 | 81.45 | 54.23 |
| R1225ye(Z) | 1.738 | 2.235 | 0.3091 | 1.845 | 31.20 | 19.06 | 0.7352 | 1.693 | 0.3713 | 83.0 | 54.23 |
| R1234yf | 1.606 | 2.501 | 0.2856 | 1.845 | 33.77 | 19.06 | 0.6657 | 1.974 | 0.3362 | 88.0 | 54.23 |
| R134a | 1.841 | 2.099 | 0.3227 | 1.845 | 29.89 | 19.06 | 0.7184 | 1.715 | 0.3628 | 84.12 | 54.23 |
| R245fa | 1.944 | 1.892 | 0.3458 | 1.845 | 27.90 | 19.06 | 0.7489 | 1.715 | 0.3782 | 82.12 | 54.23 |

*Table-6(c) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle evaporator (T_Evap_LTC) at = -75ºC and following ecofriendly ultra low GWP refrigerants in higher temperature cycle forT_Evap_HTC) at -20ºC, (T_Cond=55ºC), and sub cooling at -50ºC), isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Ecofriendly Refrigerants | HTC 1st Law Eff (COPHTC) | HTC EDR | HTC 2nd law (Exergetic) Efficiency | LTC 1st law Eff | HTC work kW | LTC work "kW" | Cascade 1st law eff Cascade COP_ Cas | Cascade Exergetic Eff | Cascade EDR | HTC Q_Cond "kW" | LTC Q_Cond= Q_EVA_HTC "kW" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.029 | 1.771 | 0.3609 | 1.868 | 26.61 | 18.83 | 0.7741 | 0.3909 | 1.558 | 80.6 | 53.43 |
| R1234ze(E) | 1.767 | 2.183 | 0.3142 | 1.868 | 30.56 | 18.83 | 0.7121 | 0.3595 | 1.781 | 84.56 | 53.43 |
| R1243zf | 1.779 | 2.160 | 0.3165 | 1.868 | 30.35 | 18.83 | 0.7152 | 0.3612 | 1.768 | 84.34 | 53.43 |
| R-1233yd(E) | 1.992 | 1.822 | 0.3543 | 1.868 | 27.1 | 18.83 | 0.7657 | 0.3867 | 1.822 | 81.09 | 53.43 |
| HFO1336mzz(Z) | 1.88 | 1.99 | 0.3343 | 1.868 | 28.71 | 18.83 | 0.7398 | 0.3736 | 1.677 | 82.71 | 53.43 |
| R1234yf | 1.606 | 2.501 | 0.2856 | 1.868 | 33.82 | 18.83 | 0.6705 | 0.3387 | 1.953 | 87.61 | 53.43 |
| R134a | 1.814 | 2.099 | 0.3227 | 1.868 | 29.76 | 18.83 | 0.7238 | 0.3656 | 1.736 | 83.75 | 53.43 |
| R245fa | 1.944 | 1.892 | 0.3458 | 1.868 | 27.77 | 18.83 | 0.7547 | 0.3811 | 1.624 | 81.77 | 53.43 |

Table-8, shows the effect of subcooling at condenser outlet on the system performances of cascaded vapour compression refrigeration system using R1234ze(Z) in high temperature circuit and HFO1336mzz(Z) in low temperature cycle evaporator (T_Evap_LTC) at = -95ºC and following ecofriendly ultra-low GWP refrigerants in HTC for T_Evap_HTC) at -30ºC, and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC) it was found that sub cooling temperature increases, the overall cascaded COP is increases and also HTC Energy Efficiency (COP) and exergetic efficiency is increases because high temperature compressor work and mass flow rate in HTC is decreases. Also heat rejected by HTC condenser and EDR of HTC and whole system is decreases.

*Table-7(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T\__{Evap\_HTC}$) at -20°C, (T_Cond =50°C), and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).*

| Ecofriendly Refrigerants | HTC 1st Law Eff ($COP_{HTC}$) | HTC EDR | HTC 2nd law (Exergetic) Efficiency | LTC 1st law Eff | HTC work kW | LTC work "kW" | Cascade 1st law eff Cascade $COP\__{Cas}$ | Cascade Exergetic Eff | Cascade EDR | HTC Q_Cond "kW" | LTC Q_Cond= $Q\__{EVA\_HTC}$ "kW" | HTC Mass flow rate Kg/sec | LTC Mass flow rate Kg/sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.029 | 1.771 | 0.3609 | 1.119 | 32.81 | 31.42 | 0.5475 | 0.3691 | 1.709 | 99.39 | 66.58 | 0.4660 | 0.2777 |
| R1234ze(E) | 1.767 | 2.183 | 0.3142 | 1.119 | 37.69 | 31.42 | 0.5089 | 0.3431 | 1.915 | 104.3 | 66.58 | 0.6681 | 0.2777 |
| R1243zf | 1.779 | 2.16 | 0.3165 | 1.119 | 37.42 | 31.42 | 0.5109 | 0.3444 | 1.904 | 104.0 | 66.58 | 0.5933 | 0.2777 |
| R1233zd(E) | 1.992 | 1.822 | 0.3543 | 1.119 | 33.42 | 31.42 | 0.5424 | 0.3656 | 1.735 | 100.0 | 66.58 | 0.5194 | 0.2777 |
| R1225ye(Z) | 1.738 | 2.235 | 0..309 | 1.119 | 38.31 | 31.42 | 0.5044 | 0.340 | 1.941 | 104.9 | 66.58 | 0.7883 | 0.2777 |
| R1234yf | 1.606 | 2.501 | 0.2856 | 1.119 | 41.46 | 31.42 | 0.4825 | 0.3253 | 2.074 | 108.0 | 66.58 | 0.8305 | 0.2777 |

*Table-7(b) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R-1225ye(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T\__{Evap\_HTC}$) at -20°C, (T_Cond =50°C), and isentropic HTC&LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).*

| Ecofriendly Refrigerants | HTC 1st Law Eff ($COP_{HTC}$) | HTC EDR | HTC 2nd law (Exergetic) Efficiency | LTC 1st law Eff | HTC work kW | LTC work "kW" | Cascade 1st law eff Cascade $COP\__{Cas}$ | Cascade Exergetic Eff | Cascade EDR | HTC Q_Cond "kW" | LTC Q_Cond= $Q\__{EVA\_HTC}$ "kW" | HTC Mass flow rate Kg/sec | LTC Mass flow rate Kg/sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1234ze(Z) | 2.029 | 1.771 | 0.3609 | 1.151 | 32.81 | 30.55 | 0.5475 | 0.369 | 1.70 | 99.3 | 66.58 | 0.4660 | 0.2777 |
| R1234ze(E) | 1.767 | 2.183 | 0.3142 | 1.151 | 37.69 | 30.55 | 0.5089 | 0.343 | 1.91 | 104. | 66.58 | 0.6681 | 0.2777 |
| R1243zf | 1.779 | 2.16 | 0.3165 | 1.151 | 37.42 | 30.55 | 0.5109 | 0.344 | 1.90 | 104. | 66.58 | 0.5933 | 0.2777 |
| R1233zd(E) | 1.992 | 1.822 | 0.3543 | 1.151 | 33.42 | 30.55 | 0.5424 | 0.365 | 1.73 | 100 | 66.58 | 0.5194 | 0.2777 |
| *HFO1336mzz(Z)* | 1.88 | 1.99 | 0.3345 | 1.151 | 34.95 | 30.55 | 0.5369 | 0.361 | 1.76 | 100 | 66.58 | 0.6334 | 0.2777 |
| R1234yf | 1.606 | 2.501 | 0.2856 | 1.151 | 41.46 | 30.55 | 0.4825 | 0.325 | 2.07 | 108 | 66.58 | 0.8305 | 0.2777 |

*Table-8 Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R1234ze(Z) in HTC and HFO1336mzz(Z) in LTC evaporator ($T\_Evap_{LTC}$) at = -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T\__{Evap\_HTC}$) at -30°C, and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80% , Cooling load =35.167 kW, temperature overlapping=10°C).*

| Sub cooling temp at cond outlet °C | HTC 1st Law Eff ($COP_{HTC}$) | HTC EDR | HTC 2nd law (Exergetic) Eff | LTC 1st law Eff | HTC work kW | LTC work "kW" | Cascade 1st law eff Cascade $COP\__{Cas}$ | Cascade Exergetic Eff | Cascade EDR | Heat Rejected by HTC cond "kW" | LTC Q_Cond= $Q\__{EVA\_HTC}$ | HTC Mass flow rate Kg/sec | LTC Mass flow rate Kg/sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.552 | 1.847 | 0.3512 | 1.351 | 39.42 | 26.01 | 0.5375 | 0.3623 | 1.760 | 100.6 | 66.58 | 0.4732 | 0.2534 |
| 5 | 1.634 | 1.705 | 0.3697 | 1.351 | 37.45 | 26.01 | 0.5542 | 0.3737 | 1.677 | 98.62 | 66.58 | 0.4495 | 0.2534 |
| 10 | 1.714 | 1.577 | 0.3880 | 1.351 | 35.68 | 26.01 | 0.5701 | 0.3843 | 1.602 | 96.86 | 66.58 | 0.4283 | 0.2534 |
| 15 | 1.794 | 1.463 | 0.4061 | 1.351 | 34.10 | 26.01 | 0.5851 | 0.3945 | 1.535 | 95.27 | 66.58 | 0.4093 | 0.2534 |
| 20 | 1.873 | 1.359 | 0.4239 | 1.351 | 32.65 | 26.01 | 0.5995 | 0.4040 | 1.415 | 93.84 | 66.58 | 0.3920 | 0.2534 |
| 25 | 1.951 | 1.265 | 0.4415 | 1.351 | 31.36 | 26.01 | 0.6130 | 0.4133 | 1.420 | 92.53 | 66.58 | 0.3764 | 0.2534 |
| 30 | 2.028 | 1.179 | 0.4590 | 1.351 | 30.70 | 26.01 | 0.6260 | 0.4220 | 1.369 | 91.34 | 66.58 | 0.3621 | 0.2534 |

Table-9(a) and Table-9(b) **,** show the effect of temperature overlapping in cascaded condenser at condenser of the system performances of cascaded vapour compression refrigeration system using R1234ze(Z) in high temperature circuit and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T\__{Evap\_HTC}$) at -30°C,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C) it was found that temperature overlapping is increases , the overall cascaded COP is decreases and HTC Energy Efficiency (COP) and exergetic efficiency do not affect because high and low temperature compressors work is increases and both mass flow rate in the HTC and LTC circuit are increases mass flow rate in HTC is decreases. Also heat rejected by HTC condenser and exergy destruction ratio of HTC and whole system is increases creases is decreases

*Table-9(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R1234ze(Z) in high temperature circuit and HFO1336mzz(Z) in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -95ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T\__{Evap\_HTC}$) at -30ºC, and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Temperature Overlapping (ºC) | HTC First Law Efficiency ($COP_{HTC}$) | HTC EDR | HTC Second law (Exergetic) Efficiency | LTC First law Eff | HTC) work “kW” | LTC work “kW” | Cascade first law efficiency Cascade $COP\__{Cas}$ | Cascade Exergetic Efficiency | Cascade EDR | Heat Rejected by HTC cond-enser “kW” | LTC Q_Cond= $Q\__{EVA\_HTC}$ “kW” | HTC Mass flow rate Kg/sec | LTC Mass flow rate Kg/sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.714 | 1.577 | 0.3880 | 1.651 | 32.94 | 21.30 | 0.6483 | 0.4370 | 1.288 | 89.41 | 56.47 | 0.3954 | 0.2331 |
| 5 | 1.714 | 1.577 | 0.3880 | 1.491 | 34.27 | 23.58 | 0.6079 | 0.4098 | 1.440 | 93.01 | 58.75 | 0.4113 | 0.2428 |
| 10 | 1.714 | 1.577 | 0.3880 | 1.352 | 35.68 | 26.01 | 0.5701 | 0.3843 | 1.602 | 96.86 | 61.17 | 0.4283 | 0.2534 |
| 15 | 1.714 | 1.577 | 0.3880 | 1.229 | 37.20 | 28.61 | 0.5344 | 0.3602 | 1.776 | 101.0 | 63.76 | 0.4465 | 0.2650 |
| 20 | 1.714 | 1.577 | 0.3880 | 1.119 | 38.84 | 31.42 | 0.5006 | 0.3375 | 1.963 | 105.4 | 66.58 | 0.4662 | 0.2777 |

*Table-9(b) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R152ain high temperature circuit and HFC134a in low temperature cycle evaporator ($T\_Evap_{LTC}$) at = -95ºC and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T\__{Evap\_HTC}$) at -30ºC,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80% , Cooling load =35.167 kW, temperature overlapping=10ºC).*

| Tempera-ture Overlapping (ºC) | HTC First Law Efficiency ($COP_{HTC}$) | HTC EDR | HTC Second law (Exergetic) Eff | LTC First law Efficiency | HTC) work “kW” | LTC) work “kW” | Cascade first law efficiency Cascade $COP\__{Cas}$ | Cascade Exergetic Efficiency | Cascade EDR | Heat Rejected by HTC cond “kW” | LTC Q_Cond= $Q\__{EVA\_HTC}$ “kW” | HTC Mass flow rate Kg/sec | LTC Mass flow rate Kg/sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.669 | 1.647 | 0.3778 | 1.667 | 33.70 | 21.09 | 0.4327 | 0.3623 | 1.669 | 89.96 | 56.26 | 0.2759 | 0.1965 |
| 5 | 1.669 | 1.647 | 0.3778 | 1.509 | 35.03 | 23.30 | 0.6029 | 0.4054 | 1.460 | 93.5 | 58.47 | 0.2868 | 0.2039 |
| 10 | 1.669 | 1.647 | 0.3778 | 1.371 | 36.44 | 25.65 | 0.5664 | 0.3818 | 1.619 | 97.25 | 60.82 | 0.2983 | 0.2118 |
| 15 | 1.669 | 1.647 | 0.3778 | 1.249 | 37.94 | 28.16 | 0.5321 | 0.3587 | 1.788 | 101.3 | 63.33 | 0.3104 | 0.2204 |
| 20 | 1.669 | 1.647 | 0.3778 | 1.140 | 39.55 | 30.85 | 0.4996 | 0.3368 | 1.969 | 105.6 | 66.01 | 0.3238 | 0.2299 |

### *2.3 Thermal performances of three cascaded vapour compression refrigeration systems for ultra-low temperature applications*

The following systems have been considered for thermodynamic performance at ultralow evaporator temperature (-155ºC) of three cascaded vapour compression refrigeration system using HFO refrigerants.

*System-1*

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -30ºC and R-1225ye (Z) in MTC at evaporator temperature of -95ºC and HFO-1336mzz (Z) in LTC at evaporator temperature at -155ºC.

*System-2*

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -30ºC and 1336mzz (Z) in MTC at evaporator temperature of -95ºC and R-1225ye (Z) in LTC at evaporator temperature at -155ºC.

*System-3*

Cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -30ºC and 1225ye (Z) in MTC at evaporator temperature of -95ºC and HFO-1336mzz (Z) in LTC at evaporator temperature at -155ºC.

*System-4*

Cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -30ºC and HFO-1336mzz (Z) in MTC at evaporator temperature of -95ºC and R1225ye (Z) inLTC at evaporator temperature at -155ºC.

*System-5*

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30ºC and R-1225ye (Z) in MTC at evaporator temperature of -95ºC and HFO-1336mzz (Z) in LTC at evaporator temperature at -155ºC.

*System-6*

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30ºC and HFO-1336mzz (Z) inMTC at evaporator temperature of -95ºC and R-1225ye (Z) in LTC at evaporator temperature at -155ºC.

*System-7*

Cascaded vapour compression refrigeration system using R1233zd(E) in HTC at evaporator temperature of -30ºC and HFO-1336mzz (Z) in MTC at evaporator temperature of -95ºC and R1225ye (Z) inLTC at evaporator temperature at -155ºC.

*System-8*

Cascaded vapour compression refrigeration system using R1233zd(E) in HTC at evaporator temperature of -30ºC and 1225ye (Z) in MTC at evaporator temperature of -95ºC and HFO-1336mzz (Z) in LTC at evaporator temperature at -155ºC.

*System-9*

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30ºC and R1233zd (E) in MTC at evaporator temperature of -95ºC and R-1225ye (Z) in LTC at evaporator temperature at -155ºC.

*System-10*

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30ºC and R1233zd (E) in MTC at evaporator temperature of -95ºC and HFO-1336mzz (Z) in LTC at evaporator temperature at -155ºC. To find out the effect of system performances using R1234ze(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55ºC and subcooling at 45ºC and evaporator temperature -30ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -95ºC and following four cascaded systems (system-1to system-4) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -155ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%. it was observed that First law (energy) and second law (Exergy) performances of system-2 are highest and system- 9 is lowest is shown in Table-10(a) & Table-10(b) respectively.

*Table-10(a) Effect of system performances using R1234ze(E)ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\_Cond}$ =50ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -135ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-1 | System-2 | System-3 | System-4 | System-5 | System-6 |
|---|---|---|---|---|---|---|
| HTC First law Efficiency ($COP_{\_HTC}$) | 1.714 | 1.714 | 1.497 | 1.497 | 1.516 | 1.516 |
| MTC First law Efficiency($COP_{MTC\_}$) | 1.391 | 1.352 | 1.391 | 1.352 | 1.391 | 1.352 |
| LTC First law Efficiency($COP_{\_LTC}$) | 0.6181 | 0.6209 | 0.6181 | 0.6209 | 0.6181 | 0.6209 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.5808 | 0.5701 | 0.5355 | 0.5259 | 0.5396 | 0.5292 |
| Cascade First law Efficiency ($COP_{\_Cascade}$) | 0.1951 | 0.20 | 0.1834 | 0.188 | 0.1805 | 0.1831 |
| ExergeticEfficiency$_{_HTC}$ | 0.3880 | 0.3388 | 0.3388 | 0.3880 | 0.3431 | 0.3431 |
| Exergy Destruction Ratio ($EDR_{\_HTC}$ ) | 1.577 | 1.577 | 1.951 | 1.951 | 1.915 | 1.694 |
| Exergetic Efficiency$_{_MTC}$ | 0.3937 | 0.3992 | 0.3690 | 0.3683 | 0.3658 | 0.3711 |
| System Exergy Destruction Ratio $_{\_Two\ Stages}$ | 1.391 | 1.506 | 1.755 | 1.715 | 1.734 | 1.694 |
| ExergeticEfficiency$_{_Three_Stages}$ | 0.2927 | 0.3052 | 0.2798 | 0.2868 | 0.2814 | 0.2814 |
| Exergy Destruction Ratio ($EDR_{\_Three\_Stages}$ ) | 2.359 | 2.277 | 2.574 | 2.487 | 2.553 | 2.467 |
| Work required to run Compressor $W_{Comp\ HTC}$ “kW” | 79.35 | 77.72 | 90.87 | 89.0 | 89.74 | 87.9 |
| Work required to run Compressor $W_{Comp\ MTC}$ “kW” | 56.90 | 56.64 | 56.90 | 56.64 | 56.90 | 56.64 |
| Work required to run Compressor $W_{Comp}$“kW” | 43.96 | 41.43 | 43.96 | 41.43 | 43.96 | 41.46 |
| Exergy of Fuel$_{_Two\ Stages}$ “kW” | 136.2 | 134.4 | 147.8 | 145.6 | 146.6 | 146.6 |
| Exergy_Product$_{_Two\ Stages}$ “kW” | 53.36 | 51.64 | 53.36 | 51.64 | 53.36 | 51.64 |
| Exergy of Fuel$_{_Three\ Stages}$ “kW” | 180.2 | 175.81 | 191.7 | 187.10 | 190.6 | 190.6 |
| Exergy_Product$_{_Three\ Stages}$ “kW” | 53.64 | 53.64 | 53.64 | 53.64 | 53.64 | 53.64 |
| Condenser Heat $_{\_HTC}$ “kW” | 215.4 | 211.0 | 226.9 | 222.2 | 225.8 | 221.1 |
| HTC Evaporator load = Condenser Heat $_{\_MTC}$ “kW” | 136.0 | 133.2 | 136.0 | 133.2 | 136 | 133.2 |
| MTC Evaporator load = Condenser Heat $_{\_LTC}$ “kW” | 79.13 | 76.59 | 79.13 | 76.59 | 79.13 | 76.59 |
| MTC Evaporator load“kW” | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.9524 | 0.9329 | 1.361 | 1.33 | 1.198 | 1.176 |
| MTC Mass flow rate (kg/sec) | 0.6305 | 0.5520 | 0.6305 | 0.552 | 0.6305 | 0.552 |
| LTC Mass flow rate (kg/sec) | 0.1907 | 0.2180 | 0.1907 | 0.218 | 0.1907 | 0.1915 |

*Table-10(b) Effect of system performances using R1234ze(E)ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =50°C and evaporator temperature -10°C, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -135°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-7 | System-8 | System-9 | System-10 |
|---|---|---|---|---|
| HTC First law Efficiency ($COP_{\_HTC}$) | 1.677 | 1.677 | 1.37 | 1.37 |
| MTC First law Efficiency($COP_{MTC\_}$) | 1.391 | 1.352 | 1.391 | 1.352 |
| LTC First law Efficiency($COP_{\_LTC}$) | 0.6181 | 0.6209 | 0.6181 | 0.6209 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.5628 | 0.5734 | 0.4977 | 0.5067 |
| Cascade First law Efficiency ($COP_{\_Cascade}$) | 0.1961 | 0.1933 | 0.1801 | 0.1757 |
| ExergeticEfficiency$_{_HTC}$ | 0.3796 | 0.3796 | 0.3101 | 0.3101 |
| Exergy Destruction Ratio ($EDR_{\_HTC}$ ) | 1.634 | 1.634 | 2.225 | 2.225 |
| Exergetic Efficiency$_{_MTC}$ | 0.3942 | 0.3837 | 0.3486 | 0.3435 |
| System Exergy Destruction Ratio $_{\_Two\ Stages}$ | 1.537 | 1.573 | 1.869 | 1.911 |
| ExergeticEfficiency$_{_Three_Stages}$ | 0.3022 | 0.2948 | 0.2747 | 0.2680 |
| Exergy Destruction Ratio ($EDR_{\_Three\_Stages}$ ) | 2.309 | 2.392 | 2.641 | 2.731 |
| Work required to run Compressor $W_{Comp\ HTC}$ "kW" | 79.45 | 81.11 | 79.24 | 99.28 |
| Work required to run Compressor $W_{Comp\ MTC}$ "kW" | 56.90 | 56.64 | 56.90 | 56.64 |
| Work required to run Compressor $W_{Comp}$"kW" | 41.93 | 41.43 | 43.43 | 41.43 |
| Exergy of Fuel$_{_Two\ Stages}$ "kW" | 136.1 | 138.0 | 153.9 | 155.2 |
| Exergy_Product$_{_Two\ Stages}$ "kW" | 53.35 | 51.64 | 53.35 | 51.64 |
| Exergy of Fuel$_{_Three\ Stages}$ "kW" | 177.5 | 182.0 | 195.3 | 200.1 |
| Exergy_Product$_{_Three\ Stages}$ "kW" | 53.64 | 53.64 | 53.64 | 53.64 |
| Condenser Heat $_{\_HTC}$ "kW" | 212.7 | 217.1 | 230.5 | 235.3 |
| HTC Evaporator load = Condenser Heat $_{\_MTC}$ "kW" | 136.0 | 133.2 | 136.0 | 133.2 |
| MTC Evaporator load = Condenser Heat $_{\_LTC}$ "kW" | 79.13 | 76.59 | 79.13 | 76.59 |
| MTC Evaporator load"kW" | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 1.046 | 1.067 | 1.644 | 1.678 |
| MTC Mass flow rate (kg/sec) | 0.6305 | 0.5520 | 0.6305 | 0.552 |
| LTC Mass flow rate (kg/sec) | 0.1907 | 0.2180 | 0.1907 | 0.218 |

### *2.4 Thermal performances of three cascaded vapour compression refrigeration systems for low temperature applications*

The following systems mentioned in table-11(a) to Table-11(f) have been considered for thermodynamic performance at low evaporator temperature (-115°C) of three cascaded vapour compression refrigeration system using HFO refrigerants

*System-1*

Cascaded vapour compression refrigeration system usingR1234ze(Z) in HTC at evaporator temperature of -10°C and R1233zd (E) at evaporator temperature of -75°C in MTC and HFO-1336mzz (Z) in LTC at evaporator temperature of -115°C

*System-2*

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -10°C and R1233zd (E) R1233zd (E) at evaporator temperature of -75°C in MTC and and R1225ye (Z) in LTC at evaporator temperature of -115°C

*System-3*

Cascaded vapour compression refrigeration system usingR1234ze(Z) in HTC at evaporator temperature of -30°C and R1225ye (Z) in MTC at evaporator temperature of -75°C and HFO-1336mzz (Z) in LTC at evaporator temperature of -115°C

*System-4*

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -10°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -75°C and R1225ye (Z) in LTC at evaporator temperature of -115°C.

To find out the effect of system performances using R1234ze(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\_Cond}$ =55°C and subcooling at 45°C and evaporator temperature -10°C, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-1to system-4) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%. it was observed that First law (energy) and second law (Exergy) performances of system-1 are highest and system- 3 is lowest is shown in table-11(a).

*Table-11(a) Effect of system performances using R1234ze(Z)ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-1 | System-2 | System-3 | System-4 |
|---|---|---|---|---|
| HTC First law Efficiency ($COP\__{HTC}$) | 2.669 | 2.669 | 2.669 | 2.669 |
| MTC First law Efficiency($COP_{MTC}$ _) | 1.516 | 1.516 | 1.516 | 1.502 |
| LTC First law Efficiency($COP\__{LTC}$) | 1.045 | 1.035 | 1.009 | 1.009 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.7948 | 0.7948 | 0.7805 | 0.7752 |
| Cascade First law Efficiency ($COP\__{Cascade}$) | 0.4234 | 0.4176 | 0.4116 | 0.4150 |
| ExergeticEfficiency$__{HTC}$ | 0.3552 | 0.3552 | 0.3552 | 0.3552 |
| Exergy Destruction Ratio ($EDR\__{HTC}$ ) | 1.815 | 1.815 | 1.815 | 1.815 |
| Exergetic Efficiency$__{MTC}$ | 0.4730 | 0.4685 | 0.460 | 0.4614 |
| System Exergy Destruction Ratio $\__{Two\ Stages}$ | 1.114 | 1.135 | 1.174 | 1.165 |
| ExergeticEfficiency$__{Three_Stages}$ | 0.3751 | 0.370 | 0.3647 | 0.3678 |
| Exergy Destruction Ratio ($EDR\__{Three\_Stages}$ ) | 1.666 | 1.703 | 1.742 | 1.719 |
| Work required to run Compressor $W_{Comp\ HTC}$ “kW” | 32.23 | 32.54 | 32.87 | 32.68 |
| Work required to run Compressor $W_{Comp\ MTC}$ “kW” | 33.65 | 33.98 | 34.86 | 34.86 |
| Work required to run Compressor $W_{Comp}$“kW” | 17.19 | 17.70 | 17.70 | 17.19 |
| Exergy of Fuel$__{Two\ Stages}$ “kW” | 65.88 | 66.52 | 67.74 | 65.54 |
| Exergy_Product$__{Two\ Stages}$ “kW” | 26.44 | 26.70 | 26.70 | 26.44 |
| Exergy of Fuel$__{Three\ Stages}$ “kW” | 83.07 | 84.22 | 85.44 | 84.73 |
| Exergy_Product$__{Three\ Stages}$ “kW” | 31.16 | 31.15 | 31.13 | 31.15 |
| Condenser Heat $\__{HTC}$ “kW” | 118.2 | 119.4 | 120.6 | 119.9 |
| HTC Evaporator load = Condenser Heat $\__{MTC}$ “kW” | 86.01 | 86.85 | 87.73 | 87.22 |
| MTC Evaporator load = Condenser Heat $\__{LTC}$ “kW” | 52.36 | 52.87 | 52.87 | 52.36 |
| LTC Evaporator load“kW” | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.5498 | 0.5552 | 0.5609 | 0.5576 |
| MTC Mass flow rate (kg/sec) | 0.3438 | 0.3472 | 0.4630 | 0.4117 |
| LTC Mass flow rate (kg/sec) | 0.2203 | 0.1939 | 0.1939 | 0.2203 |

To find out the effect of system performances using R1234ze(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T\_{Cond}$ =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following four cascaded systems (system-5to system-8) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80% is shown in table-11(b) respectively.

*System-5*

*Cascaded vapour compression refrigeration system using* R1234ze(E) in HTC at evaporator temperature of -10ºC and R1233zd (E) in MTC at evaporator temperature of -75ºC and HFO-1336mzz (Z) in LTCat evaporator temperature of -115ºC.

*System-6*

*Cascaded vapour compression refrigeration system using*R1234ze(E) in HTC at evaporator temperature of -30ºC and R1233zd (E) in MTC at evaporator temperature of -75ºC and R1225ye (Z) in LTCat evaporator temperature of -115ºC

*System-7*

Cascaded vapour compression refrigeration system usingR1234ze(E) in HTC at evaporator temperature of -10ºC and R1225ye (Z) in MTC at evaporator temperature of -75ºC and HFO-1336mzz (Z) in LTCat evaporator temperature of -115ºC System-8 cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -10ºC and HFO-1336mzz (Z) in MTC at evaporator temperature of -75ºC and R1225ye (Z) inLTCat evaporator temperature of -115ºC.

Table-11(b) shows the comparisons of thermodynamic performances of system-5to system-8 using R1234ze(E) in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-5 are highest and system- 7 is lowest as shown in Table-11(b).

*Table-11(b) Effect of system performances using R1234ze(E)ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-5 | System-6 | System-7 | System-8 |
|---|---|---|---|---|
| HTC First law Efficiency ($COP_{\_HTC}$) | 2.433 | 2.433 | 2.433 | 2.433 |
| MTC First law Efficiency($COP_{MTC}$ _) | 1.556 | 1.556 | 1.516 | 1.502 |
| LTC First law Efficiency($COP_{\_LTC}$) | 1.045 | 1.035 | 1.009 | 1.009 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.7588 | 0.7588 | 0.7454 | 0.7404 |
| Cascade First law Efficiency ($COP_{\_Cascade}$) | 0.4080 | 0.4025 | 0.3968 | 0.4001 |
| ExergeticEfficiency_$_{HTC}$ | 0.3237 | 0.3237 | 0.3237 | 0.3237 |
| Exergy Destruction Ratio ($EDR_{\_HTC}$ ) | 2.089 | 2.089 | 2.089 | 2.089 |
| Exergetic Efficiency_ $_{MTC}$ | 0.4516 | 0.4472 | 0.4393 | 0.4407 |
| System Exergy Destruction Ratio _$_{Two\ Stages}$ | 1.214 | 1.236 | 1.276 | 1.269 |
| ExergeticEfficiency_$_{Three_Stages}$ | 0.3615 | 0.3566 | 0.3516 | 0.3545 |
| Exergy Destruction Ratio ($EDR_{\_Three\_Stages}$ ) | 1.766 | 1.804 | 1.844 | 1.821 |
| Work required to run Compressor $W_{Comp\ HTC}$ "kW" | 35.36 | 35.70 | 36.06 | 35.85 |
| Work required to run Compressor $W_{Comp\ MTC}$ "kW" | 33.65 | 33.98 | 34.86 | 34.86 |
| Work required to run Compressor $W_{Comp}$"kW" | 17.19 | 17.70 | 17.70 | 17.19 |
| Exergy of Fuel_ $_{Two\ Stages}$ "kW" | 69.0 | 69.68 | 70.93 | 70.71 |
| Exergy_Product_ $_{Two\ Stages}$ "kW" | 26.44 | 26.70 | 26.70 | 26.44 |
| Exergy of Fuel_ $_{Three\ Stages}$ "kW" | 86.20 | 87.38 | 88.63 | 87.9 |
| Exergy_Product_ $_{Three\ Stages}$ "kW" | 31.16 | 31.15 | 31.13 | 31.15 |
| Condenser Heat _ $_{HTC}$ "kW" | 121.4 | 122.6 | 123.8 | 123.1 |
| HTC Evaporator load = Condenser Heat _ $_{MTC}$ "kW" | 86.01 | 86.85 | 87.73 | 87.22 |
| MTC Evaporator load = Condenser Heat _ $_{LTC}$ "kW" | 52.36 | 52.87 | 52.87 | 52.36 |
| MTC Evaporator load"kW" | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.7535 | 0.7608 | 0.7686 | 0.7641 |
| MTC Mass flow rate (kg/sec) | 0.3436 | 0.3472 | 0.4630 | 0.4117 |
| LTC Mass flow rate (kg/sec) | 0.2203 | 0.1939 | 0.1939 | 0.2203 |

To find out the effect of system performances using R1224yd(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\_Cond}$ =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following four cascaded systems (system-9to system-12) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80% is shown in Table-11(c) respectively.

*System-9*

*Cascaded vapour compression refrigeration system using* R1224yd(Z) in HTC at evaporator temperature of -10ºC and R1233zd (E) in MTC at evaporator temperature of -75ºC and HFO-1336mzz (Z) in LTC at evaporator temperature of -135ºC.

*System-10*

*Cascaded vapour compression refrigeration system using* R1224yd(Z) in HTC at evaporator temperature of -10ºC and R1233zd (E) in MTC at evaporator temperature of -75ºC and R1225ye (Z) inLTC at evaporator temperature of -135ºC

*System-11*

Cascaded vapour compression refrigeration system using R1224yd(Z) in HTC at evaporator temperature of -10ºC and HFO-1336mzz (Z) in MTC at evaporator temperature of -75ºC and R1225ye (Z) inLTC at evaporator temperature of -135ºC

*System-12*

Cascaded vapour compression refrigeration system using R1224yd(Z) in HTC at evaporator temperature of -10ºC and R1225ye (Z) in MTC at evaporator temperature of -75ºC and HFO-1336mzz (Z) inLTC at evaporator temperature of -135ºC.

Table-11(c) shows the comparisons of thermodynamic performances of system-9to system-12 using R1224yd(Z) in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-9 are highest and system-12 is lowest.

*Table-11(c) Effect of system performances using* R1224yd(Z)*ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55°C and subcooling at 45°C and evaporator temperature -10°C, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-9 | System-10 | System-11 | System-12 |
|---|---|---|---|---|
| HTC First law Efficiency ($COP_{\_ HTC}$) | 2.59 | 2.59 | 2.59 | 2.59 |
| MTC First law Efficiency($COP_{MTC}$ _) | 1.556 | 1.556 | 1.516 | 1.502 |
| LTC First law Efficiency($COP_{\_ LTC}$) | 1.045 | 1.035 | 1.009 | 1.009 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.7832 | 0.7832 | 0.7692 | 0.7640 |
| Cascade First law Efficiency ($COP_{\_ Cascade}$) | 0.4184 | 0.4127 | 0.4069 | 0.4102 |
| ExergeticEfficiency$_{_HTC}$ | 0.3447 | 0.3447 | 0.3447 | 0.3447 |
| Exergy Destruction Ratio ($EDR_{\_HTC}$ ) | 1.901 | 1.901 | 1.901 | 1.901 |
| Exergetic Efficiency$_{_ MTC}$ | 0.4661 | 0.4616 | 0.4534 | 0.4547 |
| System Exergy Destruction Ratio $_{\_Two\ Stages}$ | 1.145 | 1.166 | 1.206 | 1.199 |
| ExergeticEfficiency$_{_Three_Stages}$ | 0.3708 | 0.3657 | 0.3605 | 0.3535 |
| Exergy Destruction Ratio ($EDR_{\_Three\_Stages}$ ) | 1.696 | 1.734 | 1.774 | 1.751 |
| Work required to run Compressor $W_{Comp\ HTC}$ “kW” | 33.2 | 33.53 | 33.87 | 33.67 |
| Work required to run Compressor $W_{Comp\ MTC}$ “kW” | 33.65 | 33.98 | 34.86 | 34.86 |
| Work required to run Compressor $W_{Comp}$“kW” | 17.19 | 17.70 | 17.70 | 17.19 |
| Exergy of Fuel$_{_ Two\ Stages}$ “kW” | 66.85 | 67.5 | 68.73 | 68.53 |
| Exergy_Product$_{_ Two\ Stages}$ “kW” | 26.44 | 26.70 | 26.70 | 26.44 |
| Exergy of Fuel$_{_ Three\ Stages}$ “kW” | 84.04 | 85.2 | 86.43 | 85.72 |
| Exergy_Product$_{_ Three\ Stages}$ “kW” | 31.16 | 31.15 | 31.13 | 31.15 |
| Condenser Heat $_{\_ HTC}$ “kW” | 119.2 | 120.4 | 121.6 | 120.9 |
| HTC Evaporator load = Condenser Heat $_{\_ MTC}$ “kW” | 86.01 | 86.85 | 87.73 | 87.22 |
| MTC Evaporator load = Condenser Heat $_{\_ LTC}$ “kW” | 52.36 | 52.87 | 52.87 | 52.36 |
| MTC Evaporator load“kW” | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.7293 | 0.7364 | 0.7440 | 0.7396 |
| MTC Mass flow rate (kg/sec) | 0.3438 | 0.3472 | 0.4630 | 0.4117 |
| LTC Mass flow rate (kg/sec) | 0.2203 | 0.1939 | 0.1939 | 0.2203 |

To find out the effect of system performances using R1243zfecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\_Cond}$ =55°C and sub cooling at 45°C and evaporator temperature -10°C, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-13to system-16) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80% is shown in Table-11(d) respectively.

*System-13*

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and R1233zd(E) in MTC and R1225ye (Z) in LTC.

*System-14*

Cascaded vapour compression refrigeration system usingR1243zf in HTC at evaporator temperature of -30°C andR1233zd(E) in MTC and R1225ye (Z) inLTC

*System-15*

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC and R1225ye (Z) in LTC

*System-16*

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC and R1225ye (Z) in LTC

Table-11(d) shows the comparisons of thermodynamic performances of system-13to system-16 using R1243zf in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-13 are highest and system-15 is lowest.

*Table-11(d) Effect of system performances using R124zf ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-13 | System-14 | System-15 | System-16 |
|---|---|---|---|---|
| HTC First law Efficiency ($COP\__{HTC}$) | 2.431 | 2.431 | 2.431 | 2.431 |
| MTC First law Efficiency($COP_{MTC}$ _) | 1.556 | 1.556 | 1.516 | 1.502 |
| LTC First law Efficiency($COP\__{LTC}$) | 1.045 | 1.035 | 1.035 | 1.009 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.7585 | 0.7586 | 0.7451 | 0.7401 |
| Cascade First law Efficiency ($COP\__{Cascade}$) | 0.4079 | 0.4023 | 0.3967 | 0.3999 |
| ExergeticEfficiency_$_{HTC}$ | 0.3235 | 0.3235 | 0.3235 | 0.3235 |
| Exergy Destruction Ratio ($EDR\__{HTC}$ ) | 2.091 | 2.091 | 2.091 | 2.091 |
| Exergetic Efficiency_ $_{MTC}$ | 0.4514 | 0.4470 | 0.4392 | 0.4405 |
| System Exergy Destruction Ratio _$_{Two\ Stages}$ | 1.215 | 1.237 | 1.277 | 1.270 |
| ExergeticEfficiency_$_{Three_Stages}$ | 0.3614 | 0.3565 | 0.3515 | 0.3544 |
| Exergy Destruction Ratio ($EDR\__{Three\_Stages}$ ) | 1.767 | 1.805 | 1.845 | 1.822 |
| Work required to run Compressor $W_{Comp\ HTC}$ "kW" | 35.38 | 35.73 | 36.09 | 35.88 |
| Work required to run Compressor $W_{Comp\ MTC}$ "kW" | 33.65 | 33.98 | 34.86 | 34.86 |
| Work required to run Compressor $W_{Comp}$"kW" | 17.19 | 17.70 | 17.70 | 17.19 |
| Exergy of Fuel_ $_{Two\ Stages}$ "kW" | 69.03 | 69.70 | 70.96 | 70.74 |
| Exergy_Product_ $_{Two\ Stages}$ "kW" | 26.44 | 26.70 | 26.70 | 26.44 |
| Exergy of Fuel_ $_{Three\ Stages}$ "kW" | 86.22 | 87.41 | 88.66 | 87.93 |
| Exergy_Product_ $_{Three\ Stages}$ "kW" | 31.16 | 31.15 | 31.13 | 31.15 |
| Condenser Heat _ $_{HTC}$ "kW" | 121.4 | 122.6 | 123.8 | 123.1 |
| HTC Evaporator load = Condenser Heat _ $_{MTC}$ "kW" | 86.01 | 86.85 | 87.73 | 87.22 |
| MTC Evaporator load = Condenser Heat _ $_{LTC}$ "kW" | 52.36 | 52.87 | 52.87 | 52.36 |
| MTC Evaporator load"kW" | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.6764 | 0.7830 | 0.7899 | 0.7859 |
| MTC Mass flow rate (kg/sec) | 0.3436 | 0.3472 | 0.4630 | 0.4117 |
| LTC Mass flow rate (kg/sec) | 0.2203 | 0.1939 | 0.1939 | 0.2203 |

To find out the effect of system performances using R1234yfecofriendly refrigerant in high temperature cycle at condenser temperature $T\__{Cond}$ =55ºC and sub cooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following four cascaded systems (system-17to system-20) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80% is shown in Table-11(e) respectively.

*System-17*

*Ccascaded vapour compression refrigeration system using* R1234yf in HTC and R1233zd (E) in MTC and R-1225ye (Z) in LTC.

*System-18*

Cascaded vapour compression refrigeration system using R1234yf in HTC and R1233zd (E) in MTC and HFO-1336mzz (Z) in LTC

*System-19*

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30ºC and 1225ye (Z) in MTC and HFO-1336mzz (Z) in LTC

*System-20*

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30ºC and 1225ye (Z) in MTC and HFO-1336mzz (Z) in LTC

Table-11(e) shows the comparisons of thermodynamic performances of system-17to system-20 using R1234yf in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-17 are highest and system-19 is lowest.

*Table-11(e) Effect of system performances using R1234yf ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System-17 | System-18 | System-19 | System-20 |
|---|---|---|---|---|
| HTC First law Efficiency ($COP_{\_HTC}$) | 2.276 | 2.276 | 2.276 | 2.276 |
| MTC First law Efficiency($COP_{MTC}$ _) | 1.556 | 1.556 | 1.516 | 1.502 |
| LTC First law Efficiency($COP_{\_LTC}$) | 1.035 | 1.045 | 1.009 | 1.009 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.7329 | 0.7329 | 0.7202 | 0.7154 |
| Cascade First law Efficiency ($COP_{\_Cascade}$) | 0.3925 | 0.3968 | 0.386 | 0.3891 |
| ExergeticEfficiency$_{_HTC}$ | 0.3029 | 0.3029 | 0.3029 | 0.3029 |
| Exergy Destruction Ratio ($EDR_{\_HTC}$ ) | 2.302 | 2.302 | 2.302 | 2.302 |
| Exergetic Efficiency$_{_MTC}$ | 0.4320 | 0.4362 | 0.4245 | 0.4258 |
| System Exergy Destruction Ratio $_{\_Two\ Stages}$ | 1.315 | 1.293 | 1.356 | 1.349 |
| ExergeticEfficiency$_{_Three_Stages}$ | 0.3469 | 0.3516 | 0.3420 | 0.3448 |
| Exergy Destruction Ratio ($EDR_{\_Three\_Stages}$ ) | 1.883 | 1.844 | 1.924 | 1.90 |
| Work required to run Compressor $W_{Comp\ HTC}$ “kW” | 38.16 | 37.79 | 38.55 | 38.32 |
| Work required to run Compressor $W_{Comp\ MTC}$ “kW” | 33.98 | 33.65 | 34.86 | 34.86 |
| Work required to run Compressor $W_{Comp}$“kW” | 17.7 | 17.19 | 17.70 | 17.19 |
| Exergy of Fuel$_{_Two\ Stages}$ “kW” | 72.14 | 71.44 | 73.41 | 73.18 |
| Exergy_Product$_{_Two\ Stages}$ “kW” | 26.44 | 26.70 | 26.70 | 26.44 |
| Exergy of Fuel$_{_Three\ Stages}$ “kW” | 89.84 | 88.63 | 91.11 | 90.37 |
| Exergy_Product$_{_Three\ Stages}$ “kW” | 31.16 | 31.15 | 31.13 | 31.15 |
| Condenser Heat $_{\_HTC}$ “kW” | 125.0 | 123.8 | 126.3 | 125.5 |
| HTC Evaporator load = Condenser Heat $_{\_MTC}$ “kW” | 86.85 | 86.01 | 87.73 | 87.22 |
| MTC Evaporator load = Condenser Heat $_{\_LTC}$ “kW” | 52.87 | 52.37 | 52.87 | 52.36 |
| MTC Evaporator load“kW” | 35.167 | 35.167 | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.9203 | 0.9114 | 0.9297 | 0.9242 |
| MTC Mass flow rate (kg/sec) | 0.3436 | 0.3472 | 0.4630 | 0.4117 |
| LTC Mass flow rate (kg/sec) | 0.2203 | 0.1939 | 0.1939 | 0.2203 |

To find out the effect of system performances using R1233zd(E)ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\_Cond}$=55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following two cascaded systems (system-21 & system-22) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%. Is shown in table-11(f) respectively.

*System-21*

Cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -10ºC and 1225ye (Z) in MTC and HFO-1336mzz (Z) in LTC

*System-22*

Cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -10ºC and HFO-1336mzz (Z) in MTC and and R1225ye (Z) inLTC

Table-11(f) shows the comparisons of thermodynamic performances of system-21 & system-22 using R1233zd(E) in the high temperature cycle and it was observed that second law (Exergy) performances of system-22 are higher than system-21. Although system-22 is less energy efficient than system-21 in terms of first law efficiency (COP).

*Table-11(f) Effect of system performances using R1233zd(E)ecofriendly refrigerant in high temperature cycle at condenser temperature T_Cond =55ºC and subcooling at 45ºC and evaporator temperature -10ºC, and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75ºC and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115ºC on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies =80%.*

| Performance Parameters | System 21 | System 22 |
|---|---|---|
| HTC First law Efficiency ($COP_{\_HTC}$) | 2.640 | 2.640 |
| MTC First law Efficiency($COP_{MTC\_}$) | 1.516 | 1.502 |
| LTC First law Efficiency($COP_{\_LTC}$) | 1.009 | 1.009 |
| Cascade First law Efficiency ($COP_{Cascade}$) | 0.7764 | 0.7711 |
| Cascade First law Efficiency ($COP_{\_Cascade}$) | 0.4099 | 0.4133 |
| ExergeticEfficiency$_{_HTC}$ | 0.3513 | 0.3513 |
| Exergy Destruction Ratio ($EDR_{\_HTC}$ ) | 1.846 | 1.846 |
| Exergetic Efficiency$_{_MTC}$ | 0.4576 | 0.4589 |
| System Exergy Destruction Ratio $_{\_Two\ Stages}$ | 1.145 | 1.179 |
| ExergeticEfficiency$_{_Three_Stages}$ | 0.3632 | 0.3662 |
| Exergy Destruction Ratio ($EDR_{\_Three\_Stages}$ ) | 1.753 | 1.731 |
| Work required to run Compressor $W_{Comp\ HTC}$ "kW" | 33.23 | 33.04 |
| Work required to run Compressor $W_{Comp\ MTC}$ "kW" | 34.86 | 1.846 |
| Work required to run Compressor $W_{Comp}$"kW" | 17.7 | 17.19 |
| Exergy of Fuel$_{_Two\ Stages}$ "kW" | 68.10 | 67.9 |
| Exergy_Product$_{_Two\ Stages}$ "kW" | 26.70 | 26.44 |
| Exergy of Fuel$_{_Three\ Stages}$ "kW" | 85.80 | 85.09 |
| Exergy_Product$_{_Three\ Stages}$ "kW" | 31.16 | 31.15 |
| Condenser Heat $_{\_HTC}$ "kW" | 121.0 | 120.3 |
| HTC Evaporator load = Condenser Heat $_{\_MTC}$ "kW" | 87.73 | 87.22 |
| MTC Evaporator load = Condenser Heat $_{\_LTC}$ "kW" | 52.87 | 52.36 |
| LTC Evaporator load"kW" | 35.167 | 35.167 |
| HTC Mass flow rate (kg/sec) | 0.6191 | 0.6155 |
| MTC Mass flow rate (kg/sec) | 0.463 | 0.4117 |
| LTC Mass flow rate (kg/sec) | 0.1939 | 0.2203 |

## 3. Conclusions

To see the suitability of using HFO refrigerants, the numerical computations for simple vapour compression refrigeration systems(VCRC) in the two & three stages cascaded vapour compression refrigeration system(CVCRC) have been carried to investigate the thermodynamic(energy-exergy) performances of ultra-low GWP hydrofluoroolefens (HFO) refrigerants working on vapour compression refrigeration cycle. The effect of varying temperature overlapping between cascaded condenser-evaporator (approach), and sub cooling in high temperature condenser on thermodynamic performances also been investigated for cascaded vapour compression refrigeration systems.

The output parameters computed are compressors work as exergy input ( $W_{\_Comp\_HTC}$ and $W_{\_Comp\_LTC}$), and Compressor and the coefficient of performance (COP) of HTC cycle and energy performance of cascaded vapour compression refrigeration systems($COP_{\_Cascade\_System}$) have been carried out. The second law performances (exergetic efficiency and exergy destruction ratios) of simple and cascaded vapour compression refrigeration systems have been computed Results showed that R1234ze (Z) and R1233zd(E) gives better thermodynamic performances. Than using HFC -134a. However, R1224yd (Z)of seven GWP overcome favorable thermodynamic (energy and exergy) performances, above -10ºC of evaporator can suitably replace R134a. Similarly, HFO-1336mzz(Z) also gives better energy-exergy performances as compared to HFC-134a. However, R1234yf although gives 4% to 10% lesser thermodynamic (energy and exergy) performances than using high GWP ecofriendly HFC-134a refrigerant. Therefore, these ultra-low GWP ecofriendly HFO refrigerants can serve as new alternative refrigerants for replacing HFC-134a in the vapour compression refrigeration systems for a sustainable environment.

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