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ORIGINAL ARTICLE

Cascaded VCRS using HFO and HCFO refrigerants

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Abstract

Several alternatives are available in the literature for using HFCs and HCFC refrigerants 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, thermal energy-exergy performances of simple and cascaded VCR system for low temperature applications using ecofriendly low GWPHCFOs and HFOs refrigerants in higher temperature cycle in the temperature range of 50ºC to -10ºC and also using HCFO and HFO refrigerants of low Global Warming Potential (GWP) in lower temperature cycle have been obtained. It was observed that Cascaded VCR System using HCFO-1233zd(E) in the HT cycle and HFO-1336mzz(Z) in medium temperature cycle and HFO-1225ye(Z) in LT cycle gives highest thermal first and exergy performances than HCFO-1224yd(Z) in the high temperature cycle and HFO-1225ye(Z) in medium temperature cycle and HFO-1336mzz(Z) in LT cycle. The lowest thermal performances were observed by using ecofriendly low GWP HFO-1234yf refrigerant in higher temperature cycle using ecofriendly and HFO-1225ye(Z) in medium temperature cycle and low GWP refrigerant HFO-1336mzz(Z) in LT cycle in the cascaded of VCR system

1. Introduction

Refrigeration technology is essential to human life and production. It is widely used in daily life, business, and industrial production. Refrigeration is the process of continuously drawing heat from a body that has already cooled to the ambient temperature. Several industrial and medicinal uses demand extremely low temperatures. Blood must freeze and store at a temperature of about 80 C. For particular alloy steels to undergo precipitation hardening, extremely low temperatures—such as 90 °C—are necessary. The temperature ranges of -10°C to-30°C of the typical refrigeration systems, i.e., VCR and VAR systems, render them insufficient; the refrigeration system is primarily operated between 50°C and -10°C. Its only alternative is to use cascading refrigeration cycles, which entails utilizing two distinct compression cycles that operate with different refrigerants and connecting them to evaporative achieve the condensing of low VC stage vapour through HT stage fluid [1].

1.1 Cascade VCR System for low-temperature applications

Evaporator temperatures can be lowered to as low as -70 to -80 °C by using the Cascade VCR System. The system is efficient and can reach the temperature range of standard compression refrigeration systems. The VCR system is crucial to the generation of low or ultra-low temperatures. It can be applied as a universal stand-in for the cascade VCR system's stage compression. Barış Yilmaz et al. [2] conducted a study on the viability of using artificial refrigerants instead of natural refrigerants for ultra-low temperature applications. They also compared the energy thermal performances of the two

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refrigerants while considering environmental factors. They found that when natural HC refrigerant (HC1270 in the LT cycle and HC170 in the HT cycle) is used instead of synthetic refrigerant (HFC404A in the LT cycle and R508B in the HT cycle), the COP results are about 5% higher. Additionally, a thermal model was created using EES software in the 50–100°C temperature range to investigate the effects of various designs and operation parameters on the thermal performances of the cascade systems. To generate 45–60°C waste heat, the comparative thermal performance of cascaded VCR systems using different refrigerants for cooling and heating applications have been carried out by Fatih Yilmaz Et al. [6]. In the cascaded VCRs, the working fluid HFC 134a, HFC152a, HFC32, HFO1234yf, R365mfc and HFE 7000 were used in the HT cycle, and refrigerants R744 (CO2) were used in the LT cycle. The three different mixed refrigerants: R744 in the LT cycle and R1270 in the HT cycle, R744 in the LT cycle /R717 in the HT cycle, and R744 in the LT cycle /RE170 in the HT cycle of three cascade VCR systems. A cascade refrigeration system was created by Yijian et al. [3]. LiBr/H_2O in one subsystem of a two-stage VAR, and conventional VCRs employing HFO1234yf and HFO1234ze(E) refrigerants in the second subsystem. The VAR subsystem was run by recycling the condensing heat of the VCR subsystem, using low-grade heat from renewable energy sources, and assessing thermal performance theoretically. The cascading refrigeration system's literature evaluation compares its performance to conventional refrigeration systems and demonstrates its ability to achieve an ultra-low 170oC evaporation temperature.

Using GWP refrigerants, Yousuf Alhendal et al. [4] conducted an energy and exergy analysis of VCR systems. They concluded that HFC refrigerants with a GWP of ≤ 150 and HFO/HCFO refrigerants might be enough to reduce emissions in car air conditioning systems. In addition, three low-GWP refrigerants—HFC152a, HFO1234yf, and HFO1234ze(E)—were proposed. These were contrasted with the high-GWP HFC134a that is currently in use, and it was found that the HFO refrigerant HFO1234ze(E) performs the best both energetically and exergetically. K. Logesh et al. [5] conducted a performance examination of various refrigerants in cascading VCRs, including HFC 134a/HFC23, HFC 410A/HFC 23, and HFC 404A/HC170. The impact of the LT evaporator's superheating range of 10°C and 5°C and sub cooling range of

Fatih Yilmaz et al. [7] researched the comparative thermal performance of cascading VCR systems employing various refrigerants for cooling and heating applications. Working fluids HFC 134a, HFC152a, HFC32, HFO1234yf, R365mfc, and HFE 7000 were used in the HT cycle of the cascaded VCRs, whereas refrigerants R744 (CO2) were utilized in the LT cycle. The three distinct mixed refrigerants of the three cascade VCR systems are R744 in the LT cycle and R1270 in the HT cycle, R744 in the LT cycle /R717 in the HT cycle, and R744 in the LT cycle /RE170 in the HT cycle.

A theoretical model was established by Ebru Mançuhan et al. [7] through analysis of the environmentally beneficial and energy-efficient cascade VCRS system employing various refrigerants. In the Cascade system, high global warming potential HFC404A refrigerant in the LT cycle and natural refrigerants HFC134a, HFC152a, and NH3 in the HT cycle (HTC) are replaced with CO2 (as a natural refrigerant), and the maximum COP comparison for different operating circumstances is obtained. Using eco-friendly refrigerants for low-temperature applications, R.S. Mishra [8] performed the thermal analysis of three-stage cascade VCR systems and optimized The efficiency of HFO1234ze and HFO1234yf in the heat transfer cycle, new environmentally friendly refrigerants in the cycle of intermediate temperatures, and HFC134a or HFC404a in the cycle of low temperatures (between -50oC and -100oC) was discovered. Better thermal performances are obtained with the optimal combination of HFC1234ze in the HT cycle, HFC134a in the IT cycle, and HFC404a in the LT cycle as opposed to using HFC1234yf in the HT cycle, -HFC134a in the IT cycle, and -HFC404a in the LT cycle. Comparably, utilizing HFO1234ze in the HT cycle, HFO1234yf in the IT cycle, and HFC404a in the HT cycle results in lower thermal performance than using a different combination of HFO1234ze in the HT cycle, HFC134a in the IT cycle, and HFC404a in the LT cycle.

Zhili Sun [9,10] evaluated the theoretical thermal performances of cascade VCR systems for various refrigerant couples, R41 in the LT cycle and HFO 404A in the HT cycle, and R23 in the LT cycle and HFO 404A in the HT cycle, to determine if R41 is a suitable replacement for R23. According to the calculated results, there is an ideal condenser temperature for LTC at which COP reaches its maximum value. In cascade VCR systems, under similar operating conditions, the input power of R41 in the LT cycle and HFO 404A in the HT cycle is less than that of R23 in the LT cycle. HFO 404A in the HT cycle and the optimum COP was greater than that of R23 in the LT cycle and HFO 404A in the HT cycle. Using R41 in the LT cycle, R404A in the HT cycle, R23 in the LT cycle, and HFO 404A in the HT cycle, the maximum energy efficiency of cascaded VCR systems is roughly 44% and 43%, respectively, and concluded that a more viable refrigerant combination is the cascade VCR system using R41 in the LT cycle and HFO 404A in the HT cycle than the cascade VCR system using R23 in the LT cycle and HFO 404A in the HT cycle. By taking safety, energy efficiency, and environmental considerations into account

No pure refrigerant was discovered to be suitable for replacing hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) by Zhiqiang Yang et al. [11]. Instead, a blend of R1243zf+R1234ze(Z) was introduced, possibly a long-term replacement for R134a. The drop-in test result showed improved performance over the thermal simulation's prediction. Kaida T. et al. [12] discovered that HCFO1224yd(Z) has superior thermal and environmental qualities, making it a viable substitute for HFC 245fa in high-temperature heat pumps. This is one of the most intriguing HFOs. Theoretically, the COP is maximized at 20 K for the condenser temperature, according to the thermal study conducted by Fukuda et al. [13]. The real COP, however, is different from the theoretical COP due to the increased pressure drop. Based on the irreversible losses, which were calculated with a 75°C condenser, it was determined that the HFO1234ze(Z) performs best in high-temperature applications rather than low-temperature ones (such as window air conditioners). Additionally, the importance of choosing the right refrigerant was discovered, and it was determined that mixed or blended HFO/HFC refrigerants might be utilized as R134a substitutes. Vipin Kumar et al. [15] simulated the fourth-generation refrigerant, R1243zf, in single- and double-stage VCR systems. They found that a cascade VCR system is appropriate for the given pressure limit in the double-stage VCR system and that there is an approximately 15% increase in COP and an 11.5% decrease in compression work. Single-stage VCR systems perform poorly in low-temperature cooling applications. Moreover, the effects of condenser and evaporator temperatures on COP for both systems were examined, and it was found that while COP decreases with increasing condenser temperature, it increases with evaporator temperature. Experimental research by Florian Kaufmann et al. [22] revealed that HCFO1224yd(Z) and HCFO1233zd(E) are better low-GWP substitutes for HFC245fa. Similarly, HFO1336mzz(Z) demonstrated significantly reduced system power outputs and thermal efficiency compared to the other refrigerants. Though it performs noticeably worse than HCFO-1233zd(E) and HCFO-1224yd(Z), eco-friendly HFC245fa refrigerant can nevertheless be used to obtain the highest power output and system efficiency.

2. Use of low GWP HFC and HC Refrigerants

Numerous aspects, including thermal qualities, environmental impact, safety, efficiency, compatibility, and regulatory requirements, must be taken into account when choosing refrigerants. During the choosing process, keep the following points in mind:

2.1 Thermal Properties

To satisfy the unique needs of the cooling system, the refrigerant should have appropriate boiling and condensing temperatures, heat transfer properties, and volumetric efficiency.

2.2 Environmental Impact

The effects of refrigerants on the environment are very important to take into account, especially in light of growing worries about ozone depletion and global warming. It is preferable to use refrigerants with low or zero GWP and ozone depletion potential (ODP). This promotes the use of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), two alternatives to high-GWP refrigerants.

2.3 Safety

When choosing a refrigerant, safety comes first. It is necessary to assess elements including flammability, chemical stability, and toxicity. Refrigerants ought to have safe operating properties and shouldn't seriously endanger the environment or public health.

- Energy Efficiency: The cooling system's overall performance and operating expenses are impacted by the refrigerant's energy efficiency. It is preferred to have high energy efficiency and minimal losses during heat transfer and compression.
- Compatibility: The refrigerant must to work with the lubricants, seals, gaskets, and other components that are utilized in the cooling system. Problems with compatibility might include equipment damage, leaks, or decreased system performance.
- Regulatory Compliance: It is essential to follow national and international laws and guidelines. The desire for alternatives is fueled by standards like the Montreal Protocol and local laws that mandate the phase-out or restriction of specific refrigerants.
- Cost and Availability: It is important to take into account the cost and availability of the refrigerant, taking into account its production, distribution, and servicing costs. The cooling system's viability might be impacted by the cost-effectiveness and accessibility of the refrigerant.
- Application Specifics: The needs of various cooling applications differ. When choosing a refrigerant, considerations including the operating temperature range, system size, capacity, and particular industrial requirements must be made.

2.4 R134a

Tetrafluoroethane (CF_3CH_2F), another name for is a refrigerant that belongs to the HFC family. It has becoming more and more well-liked as a substitute for the ozone-depleting R-12 CFC refrigerant. Compressors that are scroll, reciprocating, rotary screw, and centrifugal all frequently employ R134a. Because it is non-toxic, non-flammable, and non-corrosive, handling it is regarded as safe.

Modern cars' air conditioning systems make substantial use of R134a, according to the automotive industry. It is also used as a propellant in the pharmaceutical business and in the manufacturing sector for plastic foam blowing procedures.

Under typical climatic conditions, R134a exists as a gas with a boiling point that ranges from -14.9 to -26.1°C.

This refrigerant is not entirely compatible with the lubricants and mineral-based refrigerants used with R-12 because of its special qualities. As such, in order to accept R134a, design changes to the condenser and evaporator are required. The system might also necessitate using smaller hoses and adhering to rules requiring a 30% increase in control pressure. Heat pumps, business cooling equipment, residential freezers, car air conditioning systems, and other cooling applications all employ R134a as a refrigerant. It is significant to remember that, despite R134a's historical widespread use, there is a global trend towards phasing it out or limiting its use because of its modest greenhouse gas footprint. To allay worries about climate change, many nations are switching to alternative refrigerants that have less of an adverse effect on the environment. The properties of R134a:

Table 1: Thermo and environmental properties of HFC-134a

S.no	Properties	R134a
1.	Chemical Formula	CH_2FCF_3
2.	Boiling Point	-26.15 °C)
3.	Melting Point	-101.1 °C)
4.	Molecular Weight	102.03 g/mol
5.	Density	1.207 g/cm3 (at 25 °C)
6.	Vapor Pressure	683.7 kPa (at 25 °C
7.	Critical Temp	101.06 °C
8.	Critical Pressure	4.05 MPa
9.	GWP	1430 (over 100-year time horizon)
10.	ODP	negligible

2.5 Refrigerant R32

The refrigerant R32 (difluoromethane) is a member of the hydrofluorocarbon (HFC) family. When compared to other refrigerants, R32 is renowned for its great efficiency and minimal environmental impact. Compared to many other widely used refrigerants, it has a comparatively low GWP, which makes it a desirable option for lowering greenhouse gas emissions. Due to the high flammability of the refrigerant, proper safety measures and equipment meant to handle flammable refrigerants must be used during installation, maintenance, and operation. It's crucial to abide by safety rules and recommendations when handling R32.

R32 can be used in heat pumps, air conditioners, and some commercial refrigeration applications frequently employ R32 as a refrigerant. Its effectiveness and performance in these systems are influenced by its advantageous thermal features. It is important to remember that R32 cannot simply be switched out for other refrigerants; instead, equipment built for R32 compatibility or system adjustments may be necessary when making the switch.

2.6 HFC-152a

One member of the hydrofluorocarbon (HFC) family of refrigerants is R152a (1,1-Difluoroethane). R152a is distinguished from many other refrigerants by its minimal environmental impact. Compared to refrigerants with greater GWPs, it has a relatively low GWP, which helps to explain its decreased greenhouse gas emissions. Because it is non-toxic and non-flammable, this refrigerant is safer to use in a variety of applications. Because of its strong thermal qualities, it can be used in refrigeration and cooling systems. In small-scale applications including aerosol propellants, home and commercial refrigeration, and automobile air conditioning, R152a is frequently utilized as a refrigerant. Its advantageous qualities, such as its low GWP and non-flammability, make it the material of choice in certain applications.

Table 2: Thermo and environmental properties of R32

S.no	Properties	R32
1.	Chemical Formula	CH_2F_2
2.	Boiling Point	Approx. -51.6 °C
3.	Melting Point	Approx. -136 °C
4.	Molecular Weight	52.02 g/mol
5.	Density	Approx.1.97 g/cm3 (at 25 °C)
6.	Vapor Pressure	12.7 bar (at 25°C)
7.	GWP	675 (over a 100-year time horizon)
8.	ODP	0 (negligible)

Table 3: Thermo and environmental properties of HFC 152a

S.no	Properties	R152a
1.	Chemical Formula	$C_2H_4F_2$
2.	Boiling Point	Approx. -24.8 °C
3.	Melting Point	Approx. -111.7 °C
4.	Molecular Weight	66.05 g/mol
5.	Density	Approx. 1.09 g/cm3 (at 25 °C)
6.	Vapor Pressure	8.87 bar (at 25 °C)
7.	GW	124 (over a 100-year time horizon)
8.	ODP	0 (negligible)

2.7 HFC-R245fa

One member of the hydrofluorocarbon (HFC) family of refrigerants is R245fa (1,1,1,3,3-pentafluoropropane). R245fa is mostly utilised in foam insulation applications as a blowing agent. The manufacturing sector uses R245fa to produce polyurethane foam, which is used to make insulating products. Because R245fa has a greater boiling point than certain other refrigerants, it can be used in applications where medium-temperature cooling is required or where operating temperatures are higher. R245fa is safer to handle and use because it is non-flammable and has minimal toxicity. The common metals used in refrigeration systems are not corroded by R245fa. In organic Rankine cycle (ORC) systems for waste heat recovery, R245fa is utilized as a blowing agent and works as a working fluid to produce electricity from low-temperature heat sources.

Table 4: Thermo and environmental properties of R245fa

S.no	Properties	R245fa
1.	Chemical Formula	$CHF_2CH_2CF_3$
2.	Boiling Point	Approx. 15.3 °C
3.	Melting Point	Approx.-103°C
4.	Molecular Weight	134.05 g/mol
5.	Density	Approx. 1.32 g/cm^3 (at 25 °C
6.	Vapor Pressure	0.21 bar (at 25 °C)
7.	GWP	1030 (over 100-year time horizon)
8.	ODP	0 (negligible)

2.8 HFC-R227ea

Hydrofluorocarbon (HFC) R227ea (1,1,1,2,3,3,3-heptafluoropropane) is a type of refrigerant. The strong performance of R227ea in terms of heat transfer and refrigeration is well known. Because of its strong thermal qualities, it can be used in a wide range of refrigeration and cooling applications. Here are some R227ea specifics: Because of its low toxicity and non-flammability, this refrigerant is safer to use in a variety of systems. It doesn't corrode typical metals found in refrigeration apparatus. Applications include air conditioners, chillers, and industrial refrigeration frequently use R227ea. It is appropriate for medium- and high-temperature refrigeration because to its efficient operation and favourable thermal characteristics.

Table 5: Thermo and environmental of R227ea

S.no	Properties	R227ea
1.	Chemical Formula	CF_3CHFCF_3
2.	Boiling Point	Approx. -16.4 ^oC
3.	Melting Point	Approx. -133.7 ^oC
4.	Molecular Weight	170.03 g/mol
5.	Density	Approx. 1.45 g/cm^3 (at 25 ^oC
6.	Vapor Pressure	9.21 bar (at 25 ^oC)
7.	GWP	3220 (over a 100-year time horizon)
8.	ODP	0 (negligible)

3. Hydrocarbons Refrigerant R290

Propane, or R290, is a naturally occurring refrigerant that is a member of the hydrocarbon (HC) family. R290's low GWP and 0% ODP make it an environmentally benign refrigerant. It is a common, naturally occurring material that has little effect on ozone depletion or climate change. Propane is an effective refrigerant due to its superior thermal qualities. Because of its excellent heat transmission properties and great energy efficiency, it can be used in a variety of refrigeration and cooling applications. Refrigerators, freezers, air conditioners, heat pumps, and other refrigeration equipment in homes and businesses frequently use R290. Additionally, it finds use in a few industrial settings, including commercial refrigeration units and cold storage facilities. Here are some R290-related details:

Table 6: Thermo and environmental properties of R290

S.no	Properties	R290
1.	Chemical Formula	C_3H_8
2.	Boiling Point	Approximately -42.1 ^oC)
3.	Melting Point	Approx -187.7 °C(-305.9 °F)
4.	Molecular Weight	44.1 g/mol
5.	Density	Approx. 0.493 g/cm3 (at 25 ^oC)
6.	Vapor Pressure	8.54 bar (at 25 ^oC)
7.	GWP	3 (over a 100-year time horizon)
8.	ODP	0 (negligible)

3.1 R600a

Isobutane, or R600a, is a naturally occurring refrigerant that is a member of the hydrocarbon (HC) family. R600a is renowned for having superior environmental characteristics. Its exceptionally low GWP indicates that, in comparison to other synthetic refrigerants, it has less effect on global warming. It is a sustainable option for refrigeration applications because it is non-toxic and does not contribute to ozone depletion. Here are some R600a-related details:

Good thermal qualities of R600a enable effective refrigeration and cooling. Because of its excellent heat transmission properties and great energy efficiency, it can be used in a variety of cooling applications. Small commercial refrigeration units, freezers, and refrigerators in homes are frequently equipped with this refrigerant. Additionally, certain heat pumps and air conditioners use it.

Table 7: Thermo and environmental properties of R600a

S.no	Properties	R600a
1.	Chemical Formula	C_4H_{10}
2.	Boiling Point	Approx.-11.7 ^oC
3.	Melting Point	Approx. -159.4 ^oC)
4.	Molecular Weight	58.12 g/mol
5.	Density	Approx. 0.551 g/cm^3 (at 25 ^oC)
6.	Vapor Pressure	3.64 bar (at 25 ^oC)
7.	GWP	3 (over 100-year time horizon)
8.	ODP	0 (negligible)

3.2 Refrigerant RE170

Dimethyl ether (DME), another name for refrigerant RE170, is an alternative refrigerant that has been gaining popularity because of its advantageous environmental characteristics. Colourless, combustible, and non-toxic, dimethyl ether (DME) is a gas. Its low GWP and 0% ODP make it an environmentally favourable refrigerant. It has no discernible effect on ozone depletion or climate change.

Table 8: Thermo and environmental properties of RE170

S.no	Properties	RE170
1.	Chemical Formula	CH_3OCH_3
2.	Boiling Point	Approx -24.8 ^oC
3.	Melting Point	Approx. -139.5 ^oC
4.	Molecular Weight	46.07 g/mol
5.	Density	Approx. 0.667 g/cm3 (at 25 ^oC
6.	Vapor Pressure	5.27 bar (at 25 ^oC)
7.	GWP	1 (over a 100-year time horizon)
8.	ODP	0 (negligible)

The following information relates to RE170 (DME): Because of its strong thermal qualities, RE170 can be used in a variety of refrigeration and cooling applications. It has outstanding heat transmission properties and good energy efficiency. The main applications for RE170 are low-temperature ones, like heat pumps, air conditioning, and commercial and industrial refrigeration. It is frequently used as a component in blends with other refrigerants and in cascade refrigeration systems.

4. Use of HCFO Refrigerants

In this paper two HCFO refrigerants are considered and their thermal performances have been observed. The details of these refrigerants are given below.

4.1 HCFO-1224yd(Z)

The refrigerant R1224yd(Z) is a member of the hydrofluoroolefin (HFO) family. The chemical name 2,3,3,3-Tetrafluoropropene is another name for it. A refrigerant with low GWPand favourable environmental properties is R1224yd(Z). It is used in a variety of cooling and refrigeration systems, such as air conditioning units, heat pumps, refrigerators, freezers, organic Rankine cycle (ORC) systems, centrifugal chillers, and industrial operations. It is the material of choice for applications where minimising environmental effect and energy consumption is important because to its high energy efficiency, low greenhouse gas footprint, and non-toxic properties. R1224yd(Z) facilitates the shift to more ecologically friendly refrigeration technology by providing sustainable cooling solutions for a variety of industries. However, when utilizing R1224yd(Z)

Table 9: Thermo and environmental properties of HCFO-1224yd (Z)

S.No	Properties	R1224yd (Z)
1.	Chemical Formula	$CF_3CF=CH_2$
2.	Boiling Point	Approx. -30 ºC)
3.	Melting Point	Approx. -110 ºC)
4.	Molecular Weight	134.02 g/mol
5.	Density	Approx. 1.24 g/cm^3 (at 25 ºC)
6.	Vapor Pressure	2.7 bar (at 25 ºC)
7.	GWP	1 (over a 100-year time horizon)
8.	ODP	0 (negligible)

4.2 HCFO-1233zd (E)

Hydrofluoroolefin (HFO) family of refrigerants includes R1233zd(E) and HFO-1233zd(E). Low-GWP refrigerant R1233zd(E) is renowned for having a superior environmental profile. Compared to other refrigerants, it has a nearly insignificant effect on global warming (GWP of less than 1). It is seen as a greener substitute for high-GWP refrigerants such as hydrofluorocarbons (HFCs). This refrigerant has good thermal qualities and is not poisonous or combustible. It is appropriate for use in many cooling and refrigeration applications and has a high energy efficiency. Heat pumps, organic Rankine cycle (ORC) systems, and centrifugal chillers are common applications for R1233zd(E). Because of its little environmental impact, it is a recommended option for applications where cutting energy use and greenhouse gas emissions is a top priority. Here are some details about R1233zd(E):

Table 10: Thermo and environmental properties of R1233zd (E)

S.No	Properties	R1233zd (E)
1.	Chemical Formula	$CF_3CF=CHCF_3$
2.	Boiling Point	Approx. 27.9 ºC
3.	Melting Point	Approximately -104.2 ºC
4.	Molecular Weight	114.04 g/mol
5.	Density	1.16 g/cm3 (at 25 ºC)
6.	Vapor Pressure	0.61 bar (at 25 ºC)
7.	GWP	Less than 1 (negligible)
8.	ODP	0 (negligible)

4.3 Refrigerant R1234yf

It is safe for use in a variety of applications because it is not flammable under typical operating circumstances. The main application for R1234yf is in vehicle air conditioning systems. Because of its less harmful effects on the environment, it has been chosen to replace the R-134a refrigerant. R1234yf is now the standard refrigerant for new automobiles and complies with laws intended to reduce greenhouse gas emissions.

Table 11: Thermo and environmental properties of R1234yf

S.no	Properties	R1234yf
1.	Chemical Formula	$CH_2=CFCF_3$
2.	Boiling Point	Approx. -26.3 ºC
3.	Melting Point	Approx. -30.6 °C
4.	Molecular Weight	114.04 g/mol
5.	Density	Approx. 1.16 g/cm^3 (at 25 ºC)
6.	Vapor Pressure	1.18 bar (at 25 ºC)
7.	GWP	1 (over a 100-year time horizon)
8.	ODP	0 (negligible)

4.4 Refrigerant R1234ze(E)

A member of the hydrofluoroolefin (HFO) family of refrigerants is R1234ze(E). Because of its low global warming potential, R1234ze(E) is seen as a sustainable substitute for refrigerants with high GWP. Compared to other refrigerants, it has a nearly insignificant effect on global warming (GWP of less than 1). Environmentally friendly R1234ze(E) is utilised in cooling and refrigeration systems. In addition to being non-toxic and non-flammable, R1234ze(E) has good thermal qualities. It is appropriate for use in a variety of applications where cutting energy use and greenhouse gas emissions is a top priority due to its excellent energy efficiency. Air conditioning systems, heat pumps, chillers, and other cooling applications frequently use R1234ze(E). It is a preferred option in the commercial and industrial sectors due to its favourable features and low environmental impact.

Table 12: Thermo and environmental properties of R1234ze(E)

S.no	Properties	R1234ze(E)
1.	Chemical Formula	$CF_3CF=CHCF_3$
2.	Boiling Point	Approx. -18.5 ºC)
3.	Melting Point	Approx.-103.8 ºC)
4.	Molecular Weight	114.04 g/mol
5.	Density	Approx.1.28 g/cm3 (at 25 ºC)
6.	Vapor Pressure	1.2 bar (at 25 ºC)
7.	GWP	Less than 1 (negligible)
8.	ODP	0 (negligible)

4.5 Refrigerant R1234ze(Z)

The hydrofluoroolefin (HFO) family of refrigerants includes R1234ze(Z). It is environmentally friendly and has a low global warming potential. Compared to other refrigerants, it has a nearly insignificant effect on global warming (GWP of less than 1). It is utilised in situations where environmental concerns are crucial and is regarded as a sustainable substitute for high-GWP refrigerants. This refrigerant is acceptable to use in a variety of cooling and refrigeration applications because it is non-toxic and non-flammable. It delivers great energy efficiency and strong thermal qualities. Air conditioning systems, heat pumps, chillers, and other cooling applications frequently use R1234ze(Z). It is appropriate for both the commercial and industrial sectors due to its favourable features and low environmental effect. Here are some details about R1234ze(Z):

Table 13: Thermo and environmental properties of R1234ze(Z)

S.no	Properties	R1234ze(Z)
1.	Chemical Formula	$CF_3CH{=}CHCF_3$
2.	Boiling Point	Approx -19.7 °C)
3.	Melting Point	Approx. -120 °C
4.	Molecular Weight	114.04 g/mol
5.	Density	Approximately 1.26 g/cm^3 (at 25 °C
6.	Vapor Pressure	1.09 bar (at 25 °C)
7.	GWP	Less than 1 (negligible)
8.	ODP	0

4.6 Refrigerant R1336mzz(Z)

The hydrofluoroolefin (HFO) family of refrigerants, which includes HFO-1336mzz(Z) and is also referred to as 1, 1, 1, 4, 4, 4-Hexafluoro-2 butane, is made with a low GWPand minimal environmental impact in mind. It is an environmentally friendly option for refrigeration applications because its GWP is less than 1. This refrigerant has good thermal qualities and is not poisonous or combustible. It can be applied to a variety of refrigeration and cooling systems and provides excellent energy efficiency. Applications requiring low greenhouse gas pollution and great energy efficiency, such as air conditioning systems, heat pumps, chillers, and other cooling processes, are well suited for HFO-1336mzz(Z).
Here are some details about this refrigerant:

Table 4.6 *Thermo and environmental properties* of R1336mzz(Z)

S.no	Properties	R1336mzz(Z)
1.	Chemical Formula	$C_4H_2F_6$
2.	Boiling Point	Approx. -7.4 °C
3.	Melting Point	Approximately -132 °C
4.	Molecular Weight	164.05 g/mol
5.	Density	Approx. 1.48 g/cm^3 (at 25 °C)
6.	Vapor Pressure	2.74 bar (at 25°C
7.	GWP	Less than 1 (negligible)
8.	ODP	0

4.7 Refrigerant R1243zf

2,3,3,3-Tetrafluoropropene is the chemical name of the refrigerant R1243zf. It is in the category of hydrofluoroolefin (HFO) refrigerants, which are intended to be less harmful to the environment and less likely to cause ozone depletion than conventional hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants. Here are some particulars on R1243zf:

Table 14: Thermo and environmental properties of R1243zf

S.no	Properties	R1243zf
1.	Chemical Formula	$CF_3CH{=}CHF$
2.	Boiling Point	-16.1°C)
3.	Freezing point	-111.4°C
4.	Molecular Weight	114.04 g/mol
5.	Critical temperature	89.4°C
6.	Vapor Pressure	3.75 MPa (37.5 bar)
7.	GWP	Less than 2
8.	ODP	0 (negligible)

4.8 Use of HFO+HFC blended Refrigerants

HFO and HFC blends are now a day used to replace high GWP refrigerants. Few HFO+HFC blended Refrigerants are given below.

4.8.1 Refrigerant R515A

R515A, also called 1,1,1,2,4,4,5,5,5-nonafluoropentane, is a hydrofluorocarbon (HFC) refrigerant that is utilised in a variety of cooling and refrigeration applications. It is a single-component refrigerant made entirely of nonafluoropentane (C5F9H). GWPof R515A is comparatively low when compared to numerous other widely used refrigerants. It supports attempts to mitigate climate change by providing a greener substitute for refrigerants with higher GWPs. Under typical operating conditions, R515A is thought to be non-toxic and non-flammable. Like any refrigerant, though, it's crucial to handle and store it correctly while adhering to industry standards and safety precautions. Like other widely used refrigerants, R515A is made to work efficiently when it comes to cooling. It has strong thermal characteristics and can reach the right temperatures for a range of cooling needs. Heat pumps, air conditioning systems, and commercial refrigeration are just a few of the many uses for R515A. It works with refrigeration systems that run at both medium and low temperatures. Here are some details about R515A:

Table 15: Thermo and environmental properties of R515A

S.no	Properties	R515A
1.	Chemical Formula	CF_3CFHCF_3/ C_3F4H_2
2.	Boiling Point	-18.75 °C
3.	Melting Point	-
4.	Molecular Weight	-
5.	Density	
6.	Vapor Pressure	35.55 bar
7.	GWP	387
8.	ODP	0 (negligible)

Hydrofluorocarbon (HFC) blend refrigerant R449A is used to replace ozone-depleting refrigerants like R-404A and R-22. The three primary parts of it are R-32, R-125, and R-134a. Compared to its predecessors, R449A has a lower global warming potential (GWP), which makes it a more environmentally friendly option for a variety of refrigeration and air conditioning applications. Here are some essential

R449A details:

- ***Chemical composition:*** 24.7% R-32, 24.7% R-125, and 50.6% R-134a make up the non-azeotropic combination known as R449A.
- ***Thermal Properties:*** R449A can be used in a variety of operating settings due to its advantageous thermal properties. It has outstanding heat transfer properties, a high energy efficiency, and a superior cooling capacity.
- ***Environmental Impact:*** When compared to conventional refrigerants, R449A has a much lower GWP. It's3.4. Performance and Efficiency: R449A provides a lower GWP while offering performance and efficiency comparable to R-404A. It can achieve equivalent coefficient of performance (COP) and cooling capacity in refrigeration systems, conserving energy and lessening the impact on the environment.
- ***Safety Concerns***: R449A is non-toxic and non-flammable, just like other HFC refrigerants. However, to provide enough ventilation and prevent unintentional release, basic safety procedures should be adhered to throughout handling, storage, and installation.
  R449A can be used for medium- and low-temperature refrigeration systems frequently use R449A. It is appropriate for many uses, such as industrial cooling, supermarkets, cold storage facilities, and commercial refrigeration. Additionally, R449A is compatible with both new and old equipment made for R-404A and R-22, making retrofitting simple.

4.8.2 R450A refrigerant

A blend of hydrofluoroolefin (HFO) refrigerants called R450A is used in place of conventional hydrofluorocarbon (HFC) refrigerants since it is considered to be more environmentally friendly. Here are some R450A-related details:

- ***Chemical composition:*** R-1234yf and R-134a make up the two primary components of R450A, a non-azeotropic combination. The manufacturer or supplier may have an impact on the precise composition.
- ***Environmental Impact:*** When compared to popular HFC refrigerants like R-404A and R-410A, R450A has a much lower global warming potential (GWP). Being compliant with legislation meant to mitigate climate change and assisting in the reduction of greenhouse gas emissions, it is regarded as an environmentally benign refrigerant choice.
- ***Performance and Efficiency:*** The performance and efficiency of R450A are intended to be comparable to those of the refrigerants it replaces. It ensures that refrigeration systems operate effectively while having a smaller environmental impact. It offers comparable cooling capacity and energy efficiency.
- ***Safety Considerations:*** R450A offers a safe working environment because it is regarded as non-toxic and non-flammable under typical operating settings. To guarantee safety, appropriate handling, storage, and disposal procedures must be followed, just like with any refrigerant.

Applications: The R450A has a wide range of uses in air conditioning and refrigeration. It works well with low- and medium-temperature systems, such as heat pumps, cold storage facilities, and commercial refrigeration. R450A is frequently utilised as a retrofit option since it may work with current equipment made for other refrigerants.

5. Other blends of ecofriendly refrigerants

5.1 R448A refrigerant

Refrigerant R448A, an industrial name for Opteon XP40, is a hydrofluoroolefin (HFO) blend that does not deplete the ozone layer. It is intended to be used in commercial and industrial refrigeration applications in lieu of R404A and R22. R448A is made to function at lower discharge temperatures than R404A while offering comparable cooling capacity and energy efficiency. It can assist in lowering energy usage and enhancing system functionality. The R448A is frequently utilised in a range of commercial and industrial refrigeration settings, including as cold storage facilities, food processing plants, supermarkets, and refrigerated transportation.

Here are some details about R448A:

Table 16: Thermo and environmental properties of R448A

S.no	Properties	R448A
1.	Chemical Formula	$CH_2F_2/C_2HF_5/CH_2FCF_3/$ $C_3H_2F_4/C_3H_2F_4$
2.	Boiling Point	Approx. -46°C
3.	Melting Point	-
4.	Molecular Weight	189.9 g/mol
5.	Density	-
6.	Vapor Pressure	45.94 bar
7.	GWP	1387
8.	ODP	0 (negligible)

5.2 R454C refrigerant

Chemours invented the industrial refrigerant known as R-454C. It is intended to replace high GWPrefrigerants that are frequently employed in industrial refrigeration applications with a low GWP alternative. Here are some R-454C specifics:

- ***Chemical composition:*** R-454C is a non-azeotropic blend made up of R-32, R-1234yf, and R-1234ze(E), among other hydrofluoroolefin (HFO) components. The manufacturer or supplier may have an impact on the precise composition.
- ***Environmental Impact:*** Compared to several conventional refrigerants, like R-404A and R-507A, R-454C has a much lower GWP. It significantly lowers greenhouse gas emissions, aiding in the fight against climate change. R-454C has a GWP of less than 150, which makes it a more environmentally friendly choice.
- ***Performance:*** The R-454C is made to function similarly

to the refrigerants it is meant to replace. It helps to maximise the performance of industrial refrigeration systems while reducing their negative environmental effects. It offers dependable cooling capacity and energy efficiency.

6. Results and Discussion

6.1 Effect of HFO and HCFO refrigerants on ideal thermal performance performances of three staged cascaded vapour compression refrigeration systems for ultra-low temperature application

The cascaded VCRS using HCFO-1224yd(Z) and HCFO-1233zd(E) in the HT cycle at -10ºC of evaporator temperature in the HT cycle and HCFO-1233d(E), HFO-1225ye(Z) and R1336mzz(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature in the LT cycle using HFO1225ye(Z) and HFO1336mzz(Z) ecofriendly refrigerants have been investigated and shown in Table 17 respectively and it was found that cascaded VCR System-6, using HCFO-1233zd(E) in the HT cycle at -10ºC of evaporator temperature in the HT cycle and R1336mzz(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature using HFO1225ye(Z) in the LT cycle gives best thermal performances for ultra-low temperature applications. Similarly, cascaded VCR System-5 using HCFO-1233zd(E) in the HT cycle at -10ºC of evaporator temperature in the HT cycle and R1336mzz(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature using HFO1225ye(Z) in the LT cycle gives slightly low thermal performances than system-6 for ultra-low temperature applications.

To compared the effect of HCFOs refrigerants (R1224yd(Z) and R1233zd(E) in the HT cycle and same HFO-1225ye(z) in medium temperature cycle and R1336mzz(Z) in LT cycle it was found that HCFO- 1233zd(E) in the HT cycle gives better thermal performances than using HCFO 1224yd(Z)in HT cycle as shown in Table 17, similar trend was observed in the actual thermal performances as shown in Table 18 respectively.

Table 17: Effect of HFO and HCFO refrigerants on ideal thermal performance performances of three staged cascaded vapour compression refrigeration systems (for Q_{eva_LTC}=175.0 "kW",, $T_{Sub\ cooling}$=10ºC , T_{cond_HTC}=50ºC, T_{eva_HTC}=-10ºC , $T_{overlapping\_MTC}$=10ºC , $T_{overlapping\_LTC}$=10ºC T_{eva_LTC}=-75ºC, T_{eva_LTC}=-120ºC,HTC compressor efficiency=100%, MTC compressor efficiency=100%,

Cascaded VCR System	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerant	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1233zd(E)	R1233zd(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
LTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency	0.5013	0.5095	0.4947	0.5003	0.5023	0.5079
Exergy Destruction Ratio($EDR_{Cascade}$)	1.109	1.075	1.137	1.114	1.105	1.082
$Exergy\_Efficiency_{Cascade\_VCRS}$	0.4741	0.4819	0.4679	0.4731	0.4750	0.4804
$Exergy\ of\ Fuel_{Cascade}$ "kW"	349.1	343.5	353.7	349.8	348.4	344.5
$Exergy\ of\ product_{Cascade}$ "kW"	165.5	165.5	165.5	165.5	165.5	165.5
First law $Efficiency_{Cascade\_}$	0.9691	0.9691	0.9525	0.9464	0.9716	0.9652
Exergy Destruction Ratio($EDR_{Cascade}$)	1.048	1.048	1.083	1.097	1.043	1.056
$Exergy\_Efficiency_{Cascade\_VCRS}$	0.4884	0.4884	0.480	0.4769	0.4896	0.4896
$Exergy\ of\ Fuel_{Cascade}$ "kW"	266.2	263.3	270.8	269.6	265.5	264.4
$Exergy\ of\ product_{Cascade}$ "kW"	130.0	128.6	130.0	128.6	130.0	128.6
First law Efficiency (COP_{LTC})	2.11	2.183	2.11	2.183	2.11	2.183
First law Efficiency (COP_{MTC})	1.945	1.945	1.895	1.877	1.895	1.877
First law Efficiency (COP_{HTC})	2.925	2.925	2.925	2.925	3.045	3.045
Exergy Destruction Ratio(EDR_{HTC})	1.582	1.582	1.582	1.582	1.48	1.48
$Exergy\_Efficiency_{HTC}$	0.3873	0.3873	0.3873	0.3873	0.4032	0.4032
$Exergy\ of\ Fuel_{HTC}$ "kW"	133.5	132.1	134.9	133.7	129.4	128.4
$Exergy\ of\ product_{HTC}$ "kW"	51.72	51.17	52.18	51.79	52.18	51.79
Compressor Work (W_{HTC}) "kW"	133.5	132.1	134.9	133.7	129.4	128.4
Compressor Work (W_{MTC}) "kW"	132.6	131.20	136.1	135.5	136.1	135.9
Compressor Work (W_{LTC}) "kW"	82.94	80.18	82.94	80.18	82.94	80.18
Q_{cond_HTC} "kW"	524.1	518.5	528.7	524.8	523.4	519.5
Q_{cond_MTC} "kW"	390.5	386.4	394.0	391.1	394.0	391.1
Q_{cond_LTC} "kW"	257.9	255.2	257.9	255.2	257.9	255.2
Q_{Eva_LTC} "kW"	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow Rate(Kg/sec)	3.909	3.867	3.944	3.914	3.216	3.192
MTC Mass flow Rate(Kg/sec)	1.945	1.676	2.259	2.006	2.259	2.006
LTC Mass flow Rate(Kg/sec)	0.9804	1.111	0.9804	1.111	0.9804	1.111

Table 18: Effect of HFO and HCFO refrigerants onactual thermal performance performances of three staged cascaded vapour compression refrigerants (for Q_eva_LTC=175 "kW", $T_{\_cond\_HTC}$=50ºC , $T_{\_Sub\ cooling}$=10ºC , $T_{\_cond\_HTC}$=55ºC, $T_{\_eva\_HTC}$=-10ºC , $T_{\_overlapping\_MTC}$=10ºC , $T_{\_overlapping\_LTC}$=10ºC $T_{\_eva\_LTC}$=-75ºC, $T_{\_eva\_LTC}$=-120ºC,HTC compressor efficiency=0.80, MTC compressor efficiency=0.80, LTC compressor efficiency=0.80

Cascaded VCR System	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerant	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1233zd(E)	R1233zd(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1336mzz(Z)
LTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1336mzz(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency	0.3658	0.3721	0.3650	0.3608	0.3710	0.3666
Exergy Destruction Ratio($EDR_{Cascade}$)	1.891	1.842	1.896	1.931	1.850	1.884
Exergy_Efficiency_ $_{Cascade\_VCRS}$	0.3460	0.3519	0.3452	0.3412	0.3509	0.3468
Exergy of Fuel_$_{Cascade}$ "kW"	478.4	470.3	479.4	485.1	471.7	477.3
Exergy of product$_{Cascade}$ "kW"	165.5	165.5	165.5	165.5	165.5	165.5
First law Efficiency $_{Cascade\_}$	0.7436	0.7436	0.7258	0.7306	0.7409	0.7459
Exergy Destruction Ratio($EDR_{Cascade}$)	1.669	1.669	1.734	1.716	1.678	1.661
Exergy_Efficiency_ $_{Cascade\_VCRS}$	0.3747	0.3747	0.3656	0.3682	0.3734	0.3758
Exergy of Fuel_$_{Cascade}$ "kW"	374.8	370.1	379.2	381.4	371.5	373.6
Exergy of product$_{Cascade}$ "kW"	140.4	138.7	138.7	140.4	138.7	140.4
First law Efficiency ($COP_{\_LTC}$)	1.688	1.746	1.746	1.688	1.746	1.688
First law Efficiency ($COP_{\_MTC}$)	1.556	1.556	1.502	1.516	1.502	1.516
First law Efficiency ($COP_{\_HTC}$)	2.34	2.27	2.34	2.34	2.436	2.436
Exergy Destruction Ratio($EDR_{\ HTC}$)	2.227	2.227	2.227	2.227	2.10	2.10
Exergy_Efficiency_ $_{HTC}$	0.3099	0.3099	0.3099	0.3099	0.3226	0.3226
Exergy of Fuel_ $_{HTC}$ "kW"	195.7	193.2	195.09	197.6	188.2	189.9
Exergy of product $_{HTC}$ "kW"	60.62	59.87	60.72	61.24	60.72	61.24
Compressor Work ($W_{\_HTC}$) "kW"	195.7	193.2	195.09	197.6	188.2	189.9
Compressor Work ($W_{\_MTC}$) "kW"	179.1	176.9	183.2	183.8	183.2	183.8
Compressor Work ($W_{\_LTC}$) "kW"	103.7	100.2	100.2	103.7	100.2	103.7
$Q_{\_cond\_HTC}$ "kW"	653.4	645.3	654.4	660.1	646.7	653.2
$Q_{\_cond\_MTC}$ "kW"	457.8	452.1	458.5	462.5	458.5	462.5
$Q_{\_cond\ \_LTC}$ "kW"	278.7	275.2	275.2	278.7	275.2	278.7
$Q_{\_Eva\_LTC}$ "kW"	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow Rate(Kg/sec)	4.582	4.525	4.588	4.628	3.742	3.775
MTC Mass flow Rate(Kg/sec)	1.830	1.807	2.164	2.44	1.850	2.44
LTC Mass flow Rate(Kg/sec)	0.9804	1.111	1.111	0.9804	1.111	0.9804

The cascaded VCRS using different HFOs in the HT cycle at -10ºC of evaporator temperature in the HT cycle and HCFO-1233zd(E), HFO1225ye(Z) and HFO-1336mzz(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature in the LT cycle using HFO1225ye(Z) and HFO1336mzz(Z) ecofriendly refrigerants have been investigated and shown in Table 19 to Table 21 respectively and it was found that cascaded VCR System-6, using) R1336mzz(Z) in the HT cycle at -10ºC of evaporator temperature in the HT cycle and HFO-1233zd(E in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature using HFO1225ye(Z) in the LT cycle gives best thermal performances for ultra-low temperature applications. However lowest thermal performances have been found in system-19 by using R1234yf in the HT cycle at -10ºC of evaporator temperature in the HT cycle and HFO1225ye(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature using HFO-1336mzz(Z) in the LT cycle

Table 19: Effect of HFO and HCFO refrigerants on thermal performance performances of three staged cascaded vapour compression refrigerants (for Q_eva_LTC=175 "kW", $T_{\_cond\_HTC}$=10ºC, $T_{\_Sub\ cooling}$=10ºC , $T_{\_cond\_HTC}$=55ºC, $T_{\_eva\_HTC}$=-10ºC , $T_{\_overlapping\_MTC}$=10ºC , $T_{\_overlapping\_LTC}$=10ºC $T_{\_eva\_LTC}$=-75ºC, $T_{\_eva\_LTC}$=-120ºC,HTC compressor efficiency=0.80, MTC compressor efficiency=0.80, LTC compressor efficiency=0.80

Cascaded VCR System	System-7	System-8	System-9	System-10	System-11	System-12
HTC Refrigerant	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1225ye(Z)	R1336mzz(Z)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1225ye(Z)	R1336mzz(Z)	R1233zd(E)	R1233zd(E)
LTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency	0.3476	0.3535	0.3469	0.3429	0.3435	0.3675
Exergy Destruction Ratio($EDR_{Cascade}$)	2.042	1.991	2.048	2.085	2.078	1.877
Exergy_Efficiency_ $_{Cascade\_VCRS}$	0.3288	0.3343	0.3281	0.3243	0.3249	0.3476

Exergy of Fuel_Cascade "kW"	503.6	495.1	504.5	510.4	509.4	476.2
Exergy of productCascade "kW"	165.5	165.5	165.5	165.5	165.5	165.5
First law Efficiency Cascade_	0.6970	0.6970	0.6808	0.6852	0.6869	0.7319
Exergy Destruction Ratio(EDRCascade)	1.847	1.847	1.915	1.896	1.889	1.711
Exergy_Efficiency_ Cascade_VCRS	0.3512	0.3512	0.3431	0.3453	0.3461	0.3688
Exergy of Fuel_Cascade "kW"	399.8	394.8	404.3	406.7	405.7	376.0
Exergy of productCascade "kW"	140.4	138.7	138.7	140.4	140.4	138.7
First law Efficiency (COP_LTC)	1.688	1.746	1.746	1.688	1.688	1.746
First law Efficiency (COP_MTC)	1.556	1.556	1.502	1.516	1.556	1.556
First law Efficiency (COP_HTC)	2.074	2.074	2.074	2.074	2.02	2.27
Exergy Destruction Ratio(EDR HTC)	2.640	2.640	2.640	2.640	2.738	2.326
Exergy_Efficiency_ HTC	0.2747	0.2747	0.2747	0.2747	0.2675	0.3007
Exergy of Fuel_ HTC "kW"	220.7	218.0	221.0	222.9	226.6	199.1
Exergy of product HTC "kW"	60.62	59.87	60.72	61.24	60.62	59.87
Compressor Work (W_HTC) "kW"	220.7	218.0	221.0	222.9	226.6	199.1
Compressor Work (W_MTC) "kW"	179.1	176.9	183.2	183.8	179.1	176.9
Compressor Work (W_LTC) "kW"	103.7	100.2	100.2	103.7	103.7	100.2
Q_cond_HTC "kW"	678.5	670.1	679.5	685.4	684.4	651.2
Q_cond_MTC "kW"	457.8	452.1	458.5	462.5	457.8	452.1
Q_cond _LTC "kW"	278.7	275.2	275.2	278.7	278.7	275.2
Q_Eva_LTC "kW"	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow Rate(Kg/sec)	5.005	4.943	5.013	5.056	5.973	4.594
MTC Mass flow Rate(Kg/sec)	1.830	1.807	2.164	2.44	1.830	1.807
LTC Mass flow Rate(Kg/sec)	0.9804	1.111	1.111	0.9804	0.9804	1.111

Table 20: Effect of HFO and HCFO refrigerants on thermal performance performances of three staged cascaded vapour compression refrigerants (for $Q\_eva\_LTC=175$ "kW", $T_{\_cond\_HTC}=10^oC$, $T_{\_Sub\ cooling}=10^oC$, $T_{\_cond\_HTC}=55^oC$, $T_{\_eva\_HTC}=-10^oC$, $T_{\_overlapping\_MTC}=10^oC$, $T_{\_overlapping\_LTC}=10^oC$ $T_{\_eva\_LTC}=-75^oC$, $T_{\_eva\_LTC}=-120^oC$,HTC compressor efficiency=0.80, MTC compressor efficiency=0.80, LTC compressor efficiency=0.80,

Cascaded VCR System	System-13	System-14	System-15	System-16
HTC Refrigerant	R1243zf	R1243zf	R1243zf	R1243zf
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1225ye(Z)	R1336mzz(Z)
LTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency	0.3469	0.3528	0.3462	0.3422
Exergy Destruction Ratio(EDRCascade)	2.048	1.997	2.054	2.089
Exergy_Efficiency_ Cascade_VCRS	0.3281	0.3337	0.3275	0.3237
Exergy of Fuel_Cascade "kW"	504.4	496.0	505.4	511.3
Exergy of productCascade "kW"	165.5	165.5	165.5	165.5
First law Efficiency Cascade_	0.6954	0.6954	0.6792	0.6836
Exergy Destruction Ratio(EDRCascade)	1.854	1.854	1.922	1.903
Exergy_Efficiency_ Cascade_VCRS	0.3504	0.3504	0.3423	0.3445
Exergy of Fuel_Cascade "kW"	400.7	395.8	405.7	407.7
Exergy of productCascade "kW"	140.4	138.7	138.7	140.4
First law Efficiency (COP_LTC)	1.688	1.746	1.746	1.688
First law Efficiency (COP_MTC)	1.556	1.556	1.502	1.516
First law Efficiency (COP_HTC)	2.065	2.065	2.065	2.065
Exergy Destruction Ratio(EDR HTC)	2.656	2.656	2.656	2.656
Exergy_Efficiency_ HTC	0.2735	0.2735	0.2735	0.2735
Exergy of Fuel_ HTC "kW"	221.6	218.90	222.0	223.9
Exergy of product HTC "kW"	60.62	59.87	60.72	61.24
Compressor Work (W_HTC) "kW"	221.6	218.90	222.0	223.9
Compressor Work (W_MTC) "kW"	179.1	176.9	183.2	183.8
Compressor Work (W_LTC) "kW"	103.7	100.2	100.2	103.7
Q_cond_HTC "kW"	679.4	671.4	680.4	686.3
Q_cond_MTC "kW"	457.8	452.1	458.5	462.5
Q_cond _LTC "kW"	278.7	275.2	275.2	278.7
Q_Eva_LTC "kW"	175.0	175.0	175.0	175.0
HTC Mass flow Rate(Kg/sec)	4.411	4.357	4.411	4.456
MTC Mass flow Rate(Kg/sec)	1.830	1.807	2.164	2.44
LTC Mass flow Rate(Kg/sec)	0.9804	1.111	1.118	0.9804

Table 21: Effect of HFO and HCFO refrigerants on thermal performance performances of three staged cascaded vapour compression refrigerants (for Q_eva_LTC=175 "kW", $T_{\_cond\_HTC}$=10ºC , $T_{\_Sub\ cooling}$=10ºC , $T_{\_cond\_HTC}$=55ºC, $T_{\_eva\_HTC}$=-10ºC , $T_{\_overlapping\_MTC}$=10ºC , $T_{\_overlapping\_LTC}$=10ºC $T_{\_eva\_LTC}$=-75ºC, $T_{\_eva\_LTC}$=-120ºC,HTC compressor efficiency=0.80, MTC compressor efficiency=0.80, LTC compressor efficiency=0.80,

Cascaded VCR System	System-17	System-18	System-19	System-20
HTC Refrigerant	R1234yf	R1234yf	R1234yf	R1234yf
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1225ye(Z)	R1336mzz(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency	0.3331	0.3276	0.3232	0.3269
Exergy Destruction Ratio($EDR_{Cascade}$)	2.174	2.228	2.271	2.234
Exergy_Efficiency_ $_{Cascade\_VCRS}$	0.315	0.3098	0.3057	0.3092
Exergy of Fuel_$_{Cascade}$ "kW"	525.4	534.2	541.4	535.3
Exergy of product$_{Cascade}$ "kW"	165.5	165.5	165.5	165.5
First law Efficiency $_{Cascade\_}$	0.6473	0.6954	0.6366	0.6326
Exergy Destruction Ratio($EDR_{Cascade}$)	2.066	2.066	2.117	2.137
Exergy_Efficiency_ $_{Cascade\_VCRS}$	0.3262	0.3262	0.3208	0.3188
Exergy of Fuel_$_{Cascade}$ "kW"	425.2	430.5	437.8	435.1
Exergy of product$_{Cascade}$ "kW"	138.7	140.4	140.4	138.7
First law Efficiency ($COP_{\_LTC}$)	1.746	1.688	1.688	1.746
First law Efficiency ($COP_{\_MTC}$)	1.556	1.556	1.516	1.502
First law Efficiency ($COP_{\_HTC}$)	1.821	1.821	1.821	1.821
Exergy Destruction Ratio(EDR_{HTC})	3.147	3.147	3.147	3.147
Exergy_Efficiency_ $_{HTC}$	0.2411	0.2411	0.2411	0.2411
Exergy of Fuel_ $_{HTC}$ "kW"	248.3	251.94	254.0	251.8
Exergy of product $_{HTC}$ "kW"	59.87	60.62	61.24	60.72
Compressor Work ($W_{\_HTC}$) "kW"	248.3	251.94	254.0	251.8
Compressor Work (W_M_{TC}) "kW"	176.9	179.10	183.8	183.2
Compressor Work ($W_{\_LTC}$) "kW"	100.2	103.2	103.7	103.7
$Q_{\_cond\_HTC}$ "kW"	700.4	709.2	716.4	710.3
$Q_{\_cond\_MTC}$ "kW"	452.1	457.8	462.5	458.5
$Q_{\_cond\ \_LTC}$ "kW"	275.2	278.7	278.7	275.2
$Q_{\_Eva\_LTC}$ "kW"	175.0	175.0	175.0	175.0
HTC Mass flow Rate(Kg/sec)	6.36	6.439	6.505	6.449
MTC Mass flow Rate(Kg/sec)	1.807	1.830	2.440	2.164
LTC Mass flow Rate(Kg/sec)	1.118	0.9804	0.9804	1.118

7. Conclusions and Recommendations

The following conclusions were made from thermal performances of three staged cascaded vapour compression refrigeration systems

- The cascaded VCRS using R1233zd(E) in the HT cycle at -10ºC of evaporator temperature in the high temperature cycle, -75ºC of evaporator temperature in the medium temperature cycle using R1336mzz(Z) and -120ºC of evaporator temperature in the LT cycle using R1225ye(Z) ecofriendly refrigerant gives best thermal performances for ultra-low temperature applications
- The cascaded VCRS using R1233zd(E) in the HT cycle at -10ºC of evaporator temperature in the HT cycle and R1225ye(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle 120ºC of evaporator temperature in the LT cycle using R1336mzz(Z) ecofriendly refrigerant gives better thermal performances than using R1224yd(Z) in the HT cycle at 10ºC of evaporator temperature in the HT cycle and R1225ye(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle 120ºC of evaporator temperature in the LT cycle using R1336mzz(Z) ecofriendly refrigerant and using R1224yd(Z) in the HT cycle at -10ºC of evaporator temperature in the HT cycle and R1336mzz(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle 120ºC of evaporator temperature in the LT cycle using R1225ye(Z) ecofriendly refrigerant
- The lowest thermal performances have been found by using R1234yf in the HT cycle at -10ºC of evaporator temperature in the HT cycle and HFO1225ye(Z) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle and 120ºC of evaporator temperature for low temperature applications.

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