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Thermal performance of multi cascaded vapour compression NH_3H_2O absorption systems for ultra-low temperature applications

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Abstract

In this paper, we propose three multi cascaded vapour absorption–compression refrigeration systems using low GWP ecofriendly refrigerants such as hydrocarbons, ethylene and R32 in ultra-low evaporator temperature cycle of -130ºC and R245fa and R32 in intermediate evaporator temperature cycle of -95ºC and HFO refrigerants and natural refrigerants to produce cooling capacity at -50 °C. The comparison of four cascaded systems were also carried out at -50ºC using HFC refrigerants with R717 refrigerant. It is found that multi cascaded vapour compression NH_3H_2O absorption systems using HFO-1234yf in medium temperature cycle and R245fa in intermediate temperature cycle and R32 in ultra-low temperature cycle significantly improve the thermodynamic first and second law performances as compared to simple NH_3H_2O vapour absorption refrigeration systems. It was also observed that by considering proper safety measure, the Hydrocarbon (R600a) worked well for ultra-low temperature applications for replacing R404a and R236fa

Keywords: Cascaded Vapour Absorption Compression Refrigeration Systems, Low GWP Refrigerants

1. Introduction

The use of vapour absorption refrigeration system is a talented way towards utilizing waste heat from industrial processes. LiBr absorption refrigeration system and ammonia–water absorption refrigeration systems are commonly used for low temperature applications. Even though ammonia–water absorption refrigeration system is commonly used for freezing applications with temperatures lower than 0^0 C [1]. The performance of NH_3H_2O system has low first law efficiency when the refrigeration temperature is lower than -25 °C, the thermal performance dramatically decreases. We proposed cascaded NH_3H_2O vapour absorption–compression refrigeration systems using fifteen ecofriendly refrigerants such as hydrocarbons, HFC-152a and HFO-1234yf refrigerant at -50^0 C in medium temperature cycle and R245fa in intermediate temperature cycle and R32 in ultra-low temperature cycle to produce cooling capacity at -130^0 C. Although the ultra-low temperatures for cryogenics is approaching 0 K, and its applications such as freeze drying, pharmaceuticals, chemical and petroleum industry use cascade refrigeration cycles[16-17].R.S. Mishra[14] develop an integrated solar refrigeration system where waste heat from different energy resources assists a combined vapour absorption compression system, and to analyze feasibility & practicality of that system of thermodynamically for improving its COP and exergetic efficiency by reduction of irreversibilities in terms of exergy destruction /losses occurred in the system components. The combined thermodynamic first law efficiency in terms of coefficient of performance ($COP_{\_Overall}$), second law efficiency in terms of exergetic efficiency and exergy destruction ratio based on exergy of product of a combined vapour absorption-compression system working with each of the following refrigerants in the cascaded vapour compression cycle R1234yf, R227ea, R236fa, R245fa, R143a,R134a, R32, R507 operating at -223 K evaporator temperature with temperature overlapping (Approach means the difference between cascaded condenser temperature of vapour compression cycle and evaporator temperature of vapour absorption refrigeration cycle working at 13.5 bar of highest generator pressure and 1.75 bar as lowest evaporator pressure have been presented and it is found that R141b and R245fa gives better performances.

Although the performance of vapor compression refrigeration cycle succeeds the others yet its electricity consumption is higher. Generally, the vapour compression refrigeration cycle and its configurations viz. double stage, triple stage or multistage cascade are employed for the production of low evaporation temperature at very high cooling power.

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Most of the research studies considered till date emphasize on VCR and VAR cycles (single and double effect and triple effect) and compression-absorption (combined) or cascade cycles with single or double stage. Though, exhaustive research has been carried out on cascade cycles, very less consideration has been given to explore the thermodynamic performance of VAR cycle coupled with double stages cascaded VCRS Mishra [23-24]. Additionally, none of the research work is available on thermodynamic performance analysis of multi cascaded three stages compression refrigeration cycles with absorption single effect, double and triple effect H_2O -Li/Br.

Accordingly, in the present communication, the thermodynamic and exergetic performance analysis of absorption compression (NH_3H_2O) multi three stages cascade refrigeration system for ultra low temperature is carried outhas been carried out. The analysis is performed considering NH_3H_2O in absorption system and R1234yf/R152a in medium temperature VCR system. R-245fa/R134a in intermediate temperature VCR system along with R-32 in ultra low temperature applications.

The effect of medium temperature evaporator temperature, intermediate temperature of evaporator using R1234yf,medium (-50ºC) temperature evaporator temperature, intermediate (-95ºC) temperature of evaporator using R245fa and ultra low (-130ºC) temperature evaporator temperature, intermediate temperature of evaporator using R32, hydrocarbon (i.e. R600a).The effect of temperature overlappings of multi cascaded compression NH_3H_2O vapour absorption systems , on various performance parameters viz. COP, exergetic efficiency, total exergy destruction and exergy destruction ratio (EDR).Additionally, exergy destruction and EDR of system components have been investigated.

2. Literature Review

A number of research work is devoted to thermodynamic, analyses of vapour absorption refrigeration systems

Cimset C, et.al. [1] studied compression–absorption cascaded refrigeration system used LiBr–H_2O pair first time in absorption cycle and R134a, R-410a and NH_3 fluids were used in the vapour compression cycle and found that the electrical energy consumption in the cascade refrigeration cycle is 48–51% lower than classical vapour compression refrigeration cycles that used R134a for evaporator temperature of 263 K and a condenser temperature of 313 K and by using 35% lower by using LiBr–H_2O pair for absorption cycle ,the thermal energy consumption of cascade refrigeration cycle could be reduced by 35% and also coefficient of performance (COP_cycle) was improved by 33% as compared to the NH_3–H_2O pair used in absorption cycle. The performance of cascaded VCRS also compared with using R410a and and NH_3 as working fluids .

Cimset C., et.al. [2] also studied , vapour compression-absorption system in which the NH_3-H_2O was used as fluid pair in the absorption cycle NH_3 was used in the vapour compression refrigeration cycle This two stage novel refrigeration cycle cycle was compared with other alternative cycles for the same operating conditions and found that the electrical energy consumption in this novel cycle is 58% lower than classical one stage vapour compression refrigeration cycle, 50% lower than two stage vapour compression refrigeration cycle and 25% lower than vapour compression-absorption cascade refrigeration cycle.

The thermodynamics analysis was also performed for different evaporator and generator temperatures and their results show that the thermodynamic performance of the vapour compression-absorption two stage refrigeration cycle increases with increasing generator and evaporator temperatures and found the highest exergy loss occurred in the absorber, followed by the generator and concluded that by using alternative energy sources such as solar and geothermal heat, waste and cogeneration heat with the novel two stage cycle, it is possible to obtain cooling at low temperatures. Lakdar K. & Nehdi E, [3]developed novel combined refrigeration system by using geothermal energy to supply the ammonia–water pair for the vapour absorption cycle at geothermal temperature source in the range 343–349K supplied a generator operating at 335K cascaded with conventional compression system using three working fluids (R717, R22, and R134a)., and carried out thermodynamic analysis of the cycle by the conventional compression cycle and found that the COP of a combined system is significantly higher than that of a single stage refrigeration system. Also

found that the COP can be improved by 37–54%, as compared with the conventional cycle, under the same operating conditions, i.e. evaporation temperature at 263K and a condensation temperature of 308K and concluded that for industrial refrigeration, the proposed cascaded refrigeration system constitutes an alternative solution for reducing energy consumption and greenhouse gas emissions.

Dario Colorado [4] presented a theoretical thermodynamic studies of a compression-absorption cascade refrigeration system using R134a and a lithium bromide-water solution as working fluids. The first and second law thermodynamic analyses were carried out in order to develop an advanced exergetic analysis, by splitting the total irreversibility and that of every component and found 55.4% of the irreversibility is of avoidable nature and it could be reduced and is a potential for improvement of the system and observed that the evaporator is the component in the cascaded system that shows a significant potential for improvement, followed by the cascade heat exchanger, the compressor, and finally, the generator and concluded that the results of the innovative exergetic analysis in terms of exergy destruction ratio can be very useful for future design and experimentation of these kinds of cascaded refrigeration systems.Dario Colorado[4] presented theoretical thermodynamic analysis of R744-R410a cascade refrigeration system by using operating parameters include compressor efficiency, and condensing and evaporating temperature in R410A high- and R744 low-temperature cycle and found that the performance of cascade refrigeration system in terms of COP of this system increases with the decrease of condensing temperature, and increases with the increasing evaporating temperature. Similarly the COP of this system increases with the compression efficiency.

Therefore, it can be seen that the compression efficiency, and evaporating and condensing temperature of R744-R410A cascade refrigeration system have significant effect on the COP of this system. R. Ayala, et.al. [5] studied the ammonia/lithium nitrate absorption refrigeration combined with mechanical vapour compression in the same circuit permits higher efficiencies than individual compression or absorption cycles and found 10% increase in overall efficiency using combined absorption/compression refrigeration systems. Ahmet Karakas et.al [6] carried out availability analysis for each component in the system, and found the lithium bromide/water system was found to be more effective, on the basis of both first-and second-law analyses, above 0°C than NH_3-H_2O system. Berhani G., et.al [7] carried out exergy analysis, by considering the unavoidable exergy destruction, for single, double, triple and half effect water–lithium bromide absorption cycles and obtained maximum achievable performance under the given operation conditions. The coefficient of performance (COP), the exergetic efficiencies and the exergy destruction rates are determined and the effect of the heat source temperature is evaluated and found that the COP increases significantly from double effect to triple effect cycles. The exergetic efficiency varies less among the different configurations of the cycles. In all cycles the effect of the heat source temperature on the exergy destruction rates is similar for the same type of components, while the quantitative contributions depend on type of cycle and flow configuration and concluded that the largest exergy destruction occurs in the absorbers and generators, specifically at higher heat source temperatures.

Mahmood Mastani Joybari [8] found the main limitation of conventional energy analysis for the thermal performance of energy systems is that this approach does not consider the quality of energy. On the other hand, exergy analysis not only provides information about the systems performance, but also it can specify the locations and magnitudes of losses and investigated the effect of heat transfer fluid mass flow rate and inlet temperature of the cooling water, chilled water and heat source on the outlet specific exergy and exergy destruction rate of each component and found that the lower heat transfer fluid mass flow rate is decreasing exergy destruction of the corresponding component. However, the lower temperature of heat source and chilled water inlet increases, the system exergetic efficiency. Aprhornratana S. [9] applied second law thermodynamic analysis on single-effect absorption refrigerator cycle by calculating the entropy of lithium bromide solutions and found performance parameters are strong indicators for the direction of future research. S.B. Riffat N. Shankland [10] described the integration of different types of absorption systems with vapour-compression systems. The performances of the single-effect and double-effect series and the double-effect parallel continuous absorption systems and their integration with vapour-compression systems have been carried out. Kilic and Kaynakli [11] carried out first and second law thermodynamic analysis to analyze the performance of a single stage water lithium bromide absorption refrigeration system by varying some working parameters and developed a mathematical model based on energy method and found that the performance of the ARS increases with increasing generator and evaporator temperatures but decreases with increasing condenser and absorber temperatures. Also concluded that the highest energy loss occurs in generator regardless of operating conditions and therefore it is most important component of the system. Gomri [12] carried out comparative thermodynamic analysis between single effect and double effect absorption refrigeration systems and developed the computer program using thermodynamic properties based on energy balance equations and found that for each condenser and evaporator temperature, there is an optimum generator temperature where change in energy of single effect and double effect absorption refrigeration system is minimum. They also found that the COP of double effect system is approximately twice the COP of single effect system but there is marginal difference between the energetic efficiency of the system. Yi Chena,et.al. [13] proposed a new absorption–compression refrigeration system to produce cooling energy at -30 °C to -40 °C and showed that the coefficient of performance of 0.277, which was approximately 50% higher than that of a conventional two-stage absorption refrigeration system. R.S. Mishra [14] compared three cascade vapour compression systems cascaded with evaporator of LiBr-H_2O vapour absorption refrigeration system cascaded by condenser of vapour compression refrigeration system using ecofriendly refrigerants (i.e. R1234yf, R134a, R-32, R507a, R227ea, R236fa, R245fa , R717) carried out energy and exergy analysis of all three systems and found 122% first law efficiency enhancement using triple effect VARS cascaded with VCRS and 79.45% enhancement in second law efficiency using triple effect VARS cascaded with VCRS. Similarly exergy destruction is 56.60% using triple effect VARS cascaded with VCRS and 25.9% reduction using double effect VARS cascaded with VCRS as compared with single effect. ManojDixit, A Arora & S.C. Kaushika [15] carried out thermodynamic analysis of a two stage hybrid absorption compression refrigeration system using LiBr-H_2O as working fluid. This hybrid system is compared thermodynamically with the conventional two stage absorption refrigeration system and it is found that the former can be operated at lower generator temperature and performs better than the latter. The effects of various operating parameters on thermodynamic performance indices like exergetic efficiency, area of heat exchangers and cost of the system .The heat exchangers are designed to estimate the size and cost of the system. The objective of thermo-economic optimization is the minimization of annual cost of system, which includes investment costs and exergy fuel costs and found optimized hybrid system has COP of 0.43 and exergetic efficiency of 11.68%. The optimization results in the reduction of heat exchangers area from 79.61 m² to 71.96 m² and annual cost of operation of hybrid system by 5.2%.

R.S. Mishra [16] carried out Thermal performances (first law efficiency, exergy destruction ratio & exergetic efficiency) of cascade single effect ammonia-water (NH_3-H_20) vapour absorption refrigeration system coupled with vapour compression refrigeration using ecofriendly refrigerants in the low temperature cycle of VCRS system, The combined thermodynamic first law efficiency in terms of coefficient of performance ($COP_{\_Overall}$), second law efficiency in terms of exergetic efficiency and exergy destruction ratio working with each of the following refrigerants in the cascaded vapour compression cycle R1234yf, R227ea, R236fa, R245fa, R143a,R134a, R32, R507 operating at (- 223 K) of evaporator temperature with temperature overlapping and evaporator temperature of vapour absorption refrigeration cycle working at 13.5 bar of highest generator pressure and 1.75 bar as lowest evaporator pressure have been presented and it is found thatR141b and R245fa gives better performance. R.S. Mishra [17] found that the thermodynamic performances in the case of cascaded half effect vapour absorption refrigeration system coupled with vapour compression cycle is improved by 44.6% increment of first law efficiency (i.e. over all COP), 172.87% increment of second law efficiency (i.e. exergetic efficiency) of the half effect vapour absorption refrigeration cascaded with vapour compression cycle using HFC-134a, 42.87% enhancement in first law efficiency (COP) of 142.73% increment of second law efficiency using HFO -1234yf for -50ºC of evaporator temperature of VCRS . Similarly 72.% reduction in exergy destruction ratio based on exergy of output of the half effect vapour absorption refrigeration cascaded with vapour compression cycle using HFC-134a and 70.4% reduction in exergy destruction ratio using HFO-1234yf ecofriendly refrigerant for -50ºC of evaporator temperature of VCRS. The performances of single effect cascaded vapour absorption refrigeration system coupled with vapour compression cycle significantly higher than cascaded half effect vapour absorption refrigeration coupled with vapour compression cycle. Fernández–Seara et al. [18] studied a cascade refrigeration system with a CO_2 compression vapour refrigeration system and an NH_3/H_2O absorption system at an evaporation temperature of -45 °C. and found its first law efficiency in terms of COP. Garimella and Brown [19] developed a novel cascaded absorption–compression system that coupled a single-effect $LiBr/H_2O$ absorption cycle and a subcritical CO_2 vapor–compression cycle to generate low-temperature refrigerant (-40 °C). Rogdakis and Antonopoulos [20] studied a NH_3/H_2O absorption refrigeration system driven by waste heat and predicted the theoretical COP below 0.40 when the lowest temperature is in the range of -64 °C to -30 °C. Ahmet SerhaanCanbolat& O Kaynaki [21] found triple effect absorption refrigeration system has the highest performance in terms of Coefficient of performance of this system is higher than those single and double effect absorption refrigeration systems but its structure requires many system components which make the system's structure more complex and carried out detailed thermodynamic analysis for a water lithium bromide series flow triple effect absorption refrigeration system including eight different mass flow lines based on the component temperatures. Water flows in different four lines and water – lithium bromide solution flows in different four lines in the system and found the coefficient of performance changing with varying mass flow rates. The mass flow rates of the solutions decrease with increasing temperature of the low temperature generator and also by increasing temperature of the low temperature generator has a optimistic impact on the coefficient of performance. Evaporator temperature has similar effect with low temperature generator on the system and the condenser temperature. Kaushik and Arora [22-23] carried out the energy and energy analysis of single effect and series flow double effect water–lithium bromide absorption system and developed thermal computational model for parametric investigation. Their analysis involves the effect of generator, absorber and evaporator temperatures on the energetic and energetic performance. They concluded that the irreversibility is highest in the absorber in both systems as compared to other systems. The comparison of three multi cascaded systems were also carried out at -50ºC using HFO-1234yf refrigerant and with R717 refrigerant in medium temperature cascaded cycle and using low GWP of R-245fa in intermediate temperature cycle at -95ºC and with higher GWP of R134a and R32 and compared with hydrocarbon (R600) in ultra low temperature at -130 ºC. It is found that cascaded vapour compresion absorption systems significantly improve first and second law performances as compared to simple NH_3H_2O vapour absorption refrigeration system.

2.1 System Description

Four systems using NH_3H_2O Absorption refrigeration system was cascaded with multi (three) stages of cascaded VCRS used for ultra-low temperature applications is considered in this investigation comprises of NH_3H_2O refrigeration system is in the high temperature cycle having NH_3H_2O as an absorbent and water (H_2O) as a refrigerant. The evaporator of vapour system (VARS) is coupled with the condenser of medium VCRS using HFO-1234yf as a refrigerant up to a Temperature of 223K*(i.e* -50ºC) and vapour compression refrigeration system (VCRS) is in the intermediate temperature section in which intermediate temperature is achieved using 245fa as a refrigerant up to a Temperature of 178K *(i.e.* -95ºC) in system-1, and using R32 as a refrigerant up to a temperature of 178K *(i.e.* -95ºC) in system-2 and using 134a as a refrigerant up to a Temperature of 178K *(i.e.* -95ºC) in system-3 are cascaded with vapour compression refrigeration system (VCRS) is in the intermediate temperature cycle in which ultra-low temperature is achieved using 236fa as a refrigerant up to a temperature of 143K *(i.e* -130ºC).

3. Results and Discussion

Systems chosen for comparison with using R134a in intermediate temperature cycle are low GWP ecofriendly refrigerants such as R245fa and R32 and R236fa in ultra-low temperature cycle as given below.

System-1: NH_3H_2O vapour absorption refrigeration system using cascaded HFC-152a in /medium temperature vapour compression cycle and R-245fa in intermediate/ temperature vapour compression cycle and R-32 in cascaded vapour compression low temperature cycle

System-2: NH_3H_2O vapour absorption refrigeration system using cascaded HFO-1234yf in /medium temperature vapour compression cycle and R-245fa in intermediate/ temperature vapour compression cycle and R-32 in cascaded vapour compression low temperature cycle

System-3: NH_3H_2O vapour absorption refrigeration system using cascaded HFO-1234yf in /medium temperature vapour compression cycle and R-134a in intermediate/ temperature vapour compression cycle and R-32 in cascaded vapour compression low temperature cycle

Following input variables have been chosen for validation of model

- Evaporator Temperature of NH_3H_2Ovapour absorption refrigeration system= -1°C ,
- Generator temperature=90°C.
- Evaporator Temperature of vapour compression refrigeration system in the medium temperature circuit = -50°C
- Evaporator Temperature of vapour compression refrigeration system in the intermediate temperature circuit = -95°C
- Evaporator Temperature of vapour compression refrigeration system in the low temperature circuit = --130°C
- Temperature overlapping in the vapour absorption refrigeration evaporator temperature and vapour compression refrigeration condenser temperature using R1234yf is known as overlaping_$_{MTC}$ (approach_$_{MTC}$)= 10
- Temperature overlapping in the vapour compression refrigeration evaporator temperature using R-1234yf and vapour compression refrigeration condenser temperature using R2345f is known as over-lapping_$_{ITC}$ (approach_$_{ITC}$)=10
- Temperature overlapping in the vapour compression refrigeration evaporator temperature using R-123fa and vapour compression refrigeration condenser temperature using 245fa is known as overlaping_$_{MTC}$ (Approach_$_{LTC}$)=10
- Refrigerating Capacity=29.09 "kW"
- Condenser temperature =35°C,
- Absorber Temperature=35°C,
- MTC Compressor_Efficiency=0.80,
- ITC Compressor_Efficiency=0.80,
- LTC Compressor_Efficiency=0.80,

Thermal performance of double effect vapour absorption refrigeration system using H_2O-Li/Br was computed by developed model is given below.

- First law efficiency of NH_3H_2Ovapour absorption refrigeration system is (COP_VARS) =0.322,
- (ii) The second law efficiency of vapour absorption refrigeration system is the exergetic_efficiency= 0.2475
- (iii) The exergy destruction ratio based on output(exergy of product) is EDR_$_{Output}$= 3.041
- The exergy destruction ratio based on input (exergy of exergy of fuel) is EDR_$_{Input}$=0.7525.

3.1 Effect of ultra-low evaporator temperature on percentage improvements in total thermodynamic performances of three cascaded cycles in integrated system

Table-1(a) to Table-1(c) shows the variation of intermediate temperature circuit evaporator temperature with percentage improvement in thermodynamic performances combined triple effect NH_3H_2Ovapour absorption refrigeration system cascaded with vapour compression refrigeration system using R1234yf eco-friendly refrigerant in MTC at evaporator temperature of -50ºC and R32 eco-friendly refrigerant in ITC at evaporator temperature of --95ºC and following ecofriendly refrigerants in the lower temperature cycle it was observed that as LTC evaporator temperature is increasing from (-135ºC to -120ºC), the first law efficiency (COP_overall system) of integrated vapour compression absorption system is increasing while and second law efficiency (exergetic efficiency) of cascaded vapour compression NH_3H_2O vapour absorption refrigeration system is increasing as LTC evaporator Temperature is increasing as shown in Table-1(a) to Table-1(b) respectively. . Similarly exergy destruction ratio based on exergy of product is also decreasing as LTC evaporator temperature of combined NH_3H_2O vapour absorption refrigeration system cascaded with three cascaded vapour compression refrigeration system using R236fa eco-friendly refrigerant is decreasing as shown in Table-1(c).

Table-1(a): Variation of temperature of LTC evaporator(°C) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPsof integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra lowevaporator temperature circuit for low temperature applications

Temperature of LTC Evaporator(ºC)	Overall system COP_$_{LTC}$	Overall system COP_$_{ITC}$	Overall system COP_$_{MTC}$	% improvement in Overall system COP_$_{LTC}$	% improvement in Overall system COP_$_{ITC}$	% improvement in Overall system COP_$_{MTC}$
-135	0.6392	0.5989	0.4996	98.57	86.0	55.17
-130	0.6493	0.5989	0.4996	101.7	86.0	55.17
-125	0.6494	0.5989	0.4996	104.8	86.0	55.17
-120	0.6692	0.5989	0.4996	107.8	86.0	55.17
-115	0.6787	0.5989	0.4996	110.8	86.0	55.17

Table-1(b): Variation of temperature of LTC evaporator(°C) on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

Temperature of LTC Evaporator(°C)	Overall systemExergetic Efficiency $_{LTC}$	Overall systemExergetic Efficiency $_{ITC}$	Overall systemExergetic Efficiency $_{MTC}$	% improvement in Overall system COP$_{LTC}$	% improvement in Overall systemExergetic Efficiency $_{ITC}$	% improvement in Exergetic Efficiency $_{MTC}$
-135	0.8687	0.7258	0.5284	251.0	193.9	113.6
-130	0.8899	0.7258	0.5284	259.6	193.9	113.6
-125	0.9095	0.7258	0.5284	267.5	193.9	113.6
-120	0.9271	0.7258	0.5284	274.7	193.9	113.6
-115	*0.9429*	*0.7258*	*0.5284*	*281.0*	*193.9*	*113.6*

Table-1(c): Variation of temperature of LTC evaporator(°C) on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

Temperature of LTC Evaporator(°C)	Overall system EDR$_{LTC}$	Overall system EDR$_{ITC}$	Overall system EDR$_{MTC}$	% decrement in EDR$_{LTC}$	% decrement in EDR$_{ITC}$	% decrement in EDR$_{MTC}$
-135	0.1512	0.3770	0.8924	95.03	87.68	70.65
-130	0.1237	0.3770	0.8924	95.93	87.68	70.65
-125	0.09956	0.3770	0.8924	96.73	87.68	70.65
-120	0.07859	0.3770	0.8924	97.42	87.68	70.65
-115	0.06055	0.3770	0.8924	98.01	87.68	70.65

3.2 Effect of intermediate evaporator temperature on % improvements in total thermodynamic performances of three cascaded cycles in integrated system

Table-2(a) to Table-2(c) shows the variation of intermediate temperature circuit evaporator temperature with percentage improvement in thermodynamic performances of combined NH_3H_2O vapour absorption refrigeration system cascaded with vapour compression refrigeration system using R1234yf eco-friendly refrigerant in MTC at evaporator temperature of -50°C and
R32 eco-friendly refrigerant in ITC at evaporator temperature of --95°C and following ecofriendly refrigerants in the lower temperature cycle it was observed that as ITC evaporator temperature is increasing from (-95°C to -75°C), the first law efficiency (COP_overall system) of integrated vapour compression absorption system is increasing while and second law efficiency (exergetic efficiency) of cascaded vapour compression NH_3H_2O vapour absorption refrigeration system is increasing as ITC evaporator temperature is increasing as shown in Table-2(a) to Table-2(b) respectively . Similarly exergy destruction ratio based on exergy of product is also decreasing as ITC evaporator temperature of combined NH_3H_2O vapour absorption refrigeration system cascaded with three cascaded vapour compression refrigeration system using R245fa eco-friendly refrigerant is decreasing as shown in Table-2(c).

Table-2(a): Variation of temperature of ITC evaporator (°C) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra-low evaporator temperature circuit for low temperature applications

Temperature of ITC Evaporator(°C)	Overall system COP$_{LTC}$	Overall system COP$_{ITC}$	Overall system COP$_{MTC}$	% improvement in Overall system COP$_{LTC}$	% improvement in Overall system COP$_{ITC}$	% improvement in Overall system COP$_{MTC}$
-95	0.6494	0.5989	0.4996	101.7	86.0	55.17
-90	0.6542	0.6086	0.4996	103.2	89.02	55.17
-85	0.6587	0.6184	0.4996	104.6	92.05	55.17
-80	0.6631	0.6281	0.4996	105.9	95.08	55.17
-75	0.6672	0.6379	0.4996	107.2	98.13	55.17

Table-2(b): Variation of temperature of ITC evaporator (ºC) on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra-low evaporator temperature circuit for low temperature applications

Temperature of ITC Evaporator(ºC)	Overall system Exergetic Efficiency $_{LTC}$	Overall systemExergetic Efficiency $_{ITC}$	Overall system Exergetic Efficiency $_{MTC}$	% improvement in Overall system COP$_{LTC}$	% improvement in Overall system Exergetic efficiency$_{ITC}$	% improvement in Exergetic Efficiency $_{MTC}$
-95	0.8899	0.7258	0.5284	259.6	193.3	113.5
-90	0.8796	0.7339	0.5284	255.5	196.6	113.5
-85	0.8680	0.7414	0.5284	250.7	199.6	113.5
-80	0.8551	0.7482	0.5284	245.5	202.4	113.5
-75	0.8411	0.7544	0.5284	239..9	204.8	113.5

Table-2(c): Variation of temperature of ITC evaporator (ºC) on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra-low evaporator temperature circuit for low temperature applications

Temperature of ITC Evaporator(ºC)	Overall system EDR$_{LTC}$	Overall systemEDR$_{ITC}$	Overall systemEDR$_{MTC}$	% decrement in EDR$_{LTC}$	% decrement in EDR$_{ITC}$	% decrement in EDR$_{MTC}$
-95	0.1237	0.3777	0.8924	95.93	87.58	70.65
-90	0.1368	0.3625	0.8924	95.5	88.08	70.65
-85	0.1521	0.3488	0.8924	95.0	88.53	70.65
-80	0.1695	0.3365	0.8924	94.43	88.93	70.65
-75	0.1889	0.3256	0.8924	93.79	89.29	70.65

3.3 Effect of medium evaporator temperature using on total thermodynamic performances of three cascaded cycles in integrated systems

Table-3(a) to Table-3(c) shows the variation of intermediate temperature circuit evaporator temperature with percentage improvement in thermodynamic performances combined NH_3H_2O vapour absorption refrigeration system cascaded with vapour compression refrigeration system using R1234yf eco-friendly refrigerant in medium temperature circuit evaporator temperature is increasing from (-50ºC to -20ºC), and R32 in intermediate temperature cycle at -95ºC and R236fa in ultra low evaporator temperature cycle at -130ºC and it was found that the first law efficiency (COP_system) of combined NH_3H_2O vapour absorption compression and three cascading VCR system is increasing while and second law efficiency (exergetic efficiency) of cascaded vapour compression combined NH_3H_2O vapour absorption refrigeration system is increasing as medium evaporator temperature using HFO-1234yf is increasing. Similarly exergy destruction ratio based on exergy of product is also decreasing as medium evaporator temperature circuit temperature using HFO-1234yf eco-friendly refrigerant is decreasing.

Table-3(a): Variation of temperature of MTC evaporator (ºC) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

Temperature of MTC Evaporator(ºC)	Overall system COP$_{LTC}$	Overall system COP$_{ITC}$	Overall system COP$_{MTC}$	% improvement in Overall system COP$_{LTC}$	%improvement in Overall system COP$_{ITC}$	% improvement in Overall system COP$_{MTC}$
-20	0.6852	0.6377	0.5733	112.8	98.07	78.07
-25	0.6809	0.6328	0.5610	111.5	96.53	74.24
-30	0.6760	0.6272	0.5487	110.0	94.79	70.41
-35	0.6704	0.6210	0.5364	108.2	92.86	66.58
-40	0.6640	0.6142	0.5241	106.2	90.75	62.76
-45	0.6570	0.6068	0.5118	104.1	88.46	58.95
-50	0.6494	0.5989	0.4996	101.7	86.0	55.17

Table-3(b): Variation of temperature of MTC evaporator (°C) on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

Temperature of MTC Evaporator(°C)	Overall system Exergetic Efficiency $_{LTC}$	Overall system Exergetic Efficiency $_{ITC}$	Overall system Exergetic Efficiency $_{MTC}$	% improvement in Overall system COP_$_{LTC}$	% improvement in Overall system Exergetic Efficiency $_{ITC}$	% improvement in Exergetic Efficiency $_{MTC}$
-20	0.8026	0.6295	0.5316	224.3	154.4	114.6
-25	0.8226	0.6504	0.5336	232.4	162.8	115.6
-30	0.8406	0.6695	0.5348	239.7	170.6	116.0
-35	0.8563	0.6868	0.5349	246.0	177.5	116.1
-40	0.8696	0.7019	0.5338	251.5	183.7	115.7
-45	0.8811	0.7150	0.5316	256.0	188.9	114.8
-50	0.8899	0.7258	0.5284	259.6	193.3	113.5

Table-3(c): Variation of temperature of MTC evaporator (°C) on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

Temperature of MTC Evaporator(°C)	Overall system EDR_$_{LTC}$	Overall systemEDR_$_{ITC}$	Overall systemEDR_$_{MTC}$	% decrement in EDR_$_{LTC}$	% decrement in EDR_$_{ITC}$	% decrement in EDR_$_{MTC}$
-20	0.2459	0.5885	0.8831	91.91	80.65	70.96
-25	0.2156	0.5374	0.8741	92.91	82.33	71.26
-30	0.1897	0.4935	0.8697	93.76	83.77	71.40
-35	0.1678	0.4561	0.8696	94.48	85.0	71.40
-40	0.1497	0.4246	0.8735	95.08	86.04	71.28
-45	0.1350	0.3986	0.8811	95.53	86.89	71.02
-50	0.1237	0.3777	0.8924	95.93	87.58	70.65

3.4 Effect of temperature overlapping on percentage improvements of thermodynamic performances

Table-4(a) to Table-4(c) show the variation of all three types of approaches on the percentage improvement in thermodynamic performance of combined NH_3H_2O vapour absorption refrigeration system cascaded with vapour compression refrigeration system using 1234yf ecofriendly refrigerant in medium temperature circuit and R245fa in intermediate temperature circuit and R236fa in the low temperature circuit with percentage variation of thermodynamic first and second law performances and it was observed that as temperature overlapping in increasing, the first law efficiency (COP) and second law efficiency (exergetic efficiency) of cascaded compression-Absorption systems are decreasing as temperature overlapping is increasing. Similarly exergy destruction ratio based on exergy of product is also decreasing as temperature overlapping (approach) is increasing.

Table-4(a): Variation of temperature of LTC temperature overlapping (°C) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of of integrated NH_3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

LTC Temperature overlapping (°C)	Overall system COP_$_{LTC}$	Overall system COP_$_{ITC}$	Overall system COP_$_{MTC}$	% improvement in Overall system COP_$_{LTC}$	% improvement in Overall system COP_$_{ITC}$	% improvement in Overall system COP_$_{MTC}$
0	0.6640	0.5989	0.4996	106.2	86.0	55.17
2	0.6609	0.5989	0.4996	105.3	86.0	55.17
4	0.6579	0.5989	0.4996	104.3	86.0	55.17
5	0.6564	0.5989	0.4996	103.9	86.0	55.17
6	0.6550	0.5989	0.4996	103.4	86.0	55.17
8	0.6521	0.5989	0.4996	102.5	86.0	55.17
10	0.6494	0.5989	0.4996	101.7	86.0	55.17
12	0.6467	0.5989	0.4996	100.8	86.0	55.17
14	06441	0.5989	0.4996	100.0	86.0	55.17
15	0.6428	0.5989	0.4996	99.63	86.0	55.17

Table-4(b): Variation of temperature of LTC temperature overlapping (°C) on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra-low evaporator temperature circuit for low temperature applications

LTC Temperature overlapping (°C)	Overall system Exergetic Efficiency_LTC	Overall system Exergetic Efficiency _ITC	Overall system Exergetic Efficiency _MTC	% improvement in overall system Exergetic Efficiency _MTC	% improvement in overall system Exergetic Efficiency _LTC	% improvement in overall system Exergetic Efficiency _MTC
0	0.9474	0.7258	0.5284	282.8	193.3	113.5
2	0.9351	0.7258	0.5284	277.9	193.3	113.5
4	0.9232	0.7258	0.5284	273.0	193.3	113.5
5	0.9174	0.7258	0.5284	270.7	193.3	113.5
6	0.9117	0.7258	0.5284	268.4	193.3	113.5
8	0.9006	0.7258	0.5284	263.9	193.3	113.5
10	0.8899	0.7258	0.5284	259.6	193.3	113.5
12	0.8796	0.7258	0.5284	255.5	193.3	113.5
14	0.8697	0.7258	0.5284	251.5	193.3	113.5
15	0.8649	0.7258	0.5284	249.5	193.3	113.5

Table-4(c): Variation of temperature of LTC temperature overlapping (°C) on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra-low evaporator temperature circuit for low temperature applications

LTC Temperature overlapping (°C)	Overall system EDR_LTC	Overall systemEDR_ITC	Overall systemEDR_MTC	% decrement in EDR_LTC	% decrement in EDR_ITC	% decrement in EDR_MTC
0	0.05525	0.3770	0.8924	98.17	87.5	70.65
2	0.06945	0.3770	0.8924	97.72	87.5	70.65
4	0.08324	0.3770	0.8924	97.26	87.5	70.65
5	0.09008	0.3770	0.8924	97.04	87.5	70.65
6	0.09689	0.3770	0.8924	96.81	87.5	70.65
8	0.1104	0.3770	0.8924	96.37	87.5	70.65
10	0.1237	0.3770	0.8924	95.93	87.5	70.65
12	0.1368	0.3770	0.8924	95.50	87.5	70.65
14	0.1498	0.3770	0.8924	95.07	87.5	70.65
15	0.1562	0.3770	0.8924	94.86	87.5	70.65

3.5 Effect of ITC temperature overlappings on total thermodynamic performances

Table-5(a) to Table-5(c) show the variation of all three types of approaches on thermodynamic performance and percentage improvement in thermodynamic performance of combined NH_3H_2O VARS cascaded with VCRS using 1234yf ecofriendly refrigerant in medium temperature circuit and R245fa in intermediate temperature circuit and R236fa in the low temperature. It was observed that as temperature overlapping in increasing, the COP and exergetic efficiency of cascaded compression-Absorption systems are decreasing as temperature overlapping is increasing. Similarly exergy destruction ratio based on exergy of product is also decreasing as temperature overlapping is increasing.

Table-5(a): Variation of temperature of ITC temperature overlapping (°C) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

ITC Temperature overlapping (°C)	Overall system COP_LTC	Overall system COP_ITC	Overall system COP_MTC	% improvement in Overall system COP_LTC	% improvement in Overall system COP_ITC	% improvement in Overall system COP_MTC
0	0.6685	0.6147	0.4996	107.6	90.92	
2	0.6646	0.6115	0.4996	106.4	89.91	55.17
4	0.6607	0.6082	0.4996	105.2	88.91	55.17
5	0.6588	0.6067	0.4996	104.6	88.40	55.17
6	0.6569	0.6051	0.4996	104.0	87.92	55.17
8	0.6531	0.6020	0.4996	102.8	86.96	55.17

10	0.6494	0.5989	0.4996	101.7	86.0	55.17
12	0.6457	0.5959	0.4996	100.5	85.06	55.17
14	0.6421	0.5929	0.4996	99.41	84.14	55.17
15	0.6403	0.5914	0.4996	98.85	83.68	55.17

Table-5(b): Variation of temperature of ITC temperature overlapping (°C) on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

ITC Temperature overlapping (°C)	Overall system Exergetic Efficiency_LTC	Overall system Exergetic Efficiency _ITC	Overall system Exergetic Efficiency _MTC	% improvement in overall system Exergetic Efficiency _MTC	% improvement in overall system Exergetic Efficiency _LTC	% improvement in overall system Exergetic Efficiency _MTC
0	0.9485	0.7770	0.5284	283.3	214.0	113.5
2	0.9363	0.7662	0.5284	278.4	209.6	113.5
4	0.9244	0.7557	0.5284	273.5	205.4	113.5
5	0.9185	0.7506	0.5284	271.2	203.3	113.5
6	0.9127	0.7455	0.5284	268.8	201.3	113.5
8	0.9012	0.7355	0.5284	264.2	197.2	113.5
10	0.8899	0.7258	0.5284	259.6	193.3	113.5
12	0.8789	0.7164	0.5284	255.1	189.5	113.5
14	0.8680	0.7071	0.5284	250.8	185.7	113.5
15	0.8626	0.7026	0.5284	248.6	183.9	113.5

Table-5(c): Variation of temperature of ITC temperature overlapping (°C) on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

ITC Temperature overlapping (°C)	Overall system EDR_LTC	Overall system EDR_ITC	Overall systemEDR_MTC	% decrement in EDR_LTC	% decrement in EDR_ITC	% decrement in EDR_MTC
0	0.05433	0.2870	0.8924	98.21	90.56	70.65
2	0.06804	0.3051	0.8924	97.76	89.97	70.65
4	0.08182	0.3232	0.8924	97.31	89.37	70.65
5	0.08874	0.3323	0.8924	97.08	89.07	70.65
6	0.09569	0.3414	0.8924	96.85	88.77	70.65
8	0.1096	0.3595	0.8924	96.39	88.18	70.65
10	0.1237	0.3770	0.8924	95.93	87.58	70.65
12	0.1378	0.3959	0.8924	95.47	86.98	70.65
14	0.1521	0.4142	0.8924	95.0	86.38	70.65
15	0.1592	0.4233	0.8924	94.76	86.08	70.65

3.6 Effect of MTC temperature overlappings on percentage improvements of thermodynamic performances

Table-6(a) to Table-6(c) show the variation of temperature of MTC temperature overlapping (°C) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra-low evaporator temperature circuit for low temperature applications with variation of thermodynamic first and second law performances and it was observed that as temperature overlapping in increasing, the first law efficiency (COP) and second law efficiency (exergetic efficiency) VCRS of cascaded system are decreasing as temperature overlapping is increasing as shown in Table-6(a) to Table-6(b) respectively. .Similarly exergy destruction ratio based on exergy of product is also decreasing as temperature overlapping (approach) is increasing as shown in Table-6(c) respectively. .

Table-6(a): Variation of temperature of MTC temperature overlapping (°C) on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

MTC Temperature overlapping (°C)	Overall system COP_{LTC}	Overall system COP_{ITC}	Overall system COP_{MTC}	% improvement in Overall system COP_{LTC}	% improvement in Overall system COP_{ITC}	% improvement in Overall system COP_{MTC}
0	0.6796	0.6268	0.5211	111.1	94.66	61.86
2	0.6735	0.6212	0.5168	109.2	92.92	60.50
4	0.6675	0.6156	0.5125	107.31	91.07	59.50
5	0.6645	0.6128	0.5103	106.4	90.31	58.49
6	0.6614	0.6100	0.5083	105.4	89.45	57.82
8	0.6554	0.6044	0.5039	103.6	87.72	56.49
10	0.6494	0.5989	0.4996	101.7	86.0	55.17
12	0.6433	0.5934	0.4954	99.81	84.28	53.85
14	0.6373	0.5878	0.4911	97.93	82.57	52.53
15	0.6343	0.5851	0.4890	96.99	81.71	51.87

Table-6(b): Variation of temperature of ITC temperature overlapping (°C) on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

MTC Temperature overlapping (°C)	Overall system Exergetic $Efficiency\_{LTC}$	Overall system Exergetic Efficiency $\_{ITC}$	Overall system Exergetic Efficiency $\_{MTC}$	% improvement in overall system Exergetic Efficiency $\_{MTC}$	% improvement in overall system Exergetic Efficiency $\_{LTC}$	% improvement in overall system Exergetic Efficiency $\_{MTC}$
0	0.9573	0.7891	0.5851	286.8	218.9	136.4
2	0.9436	0.7761	0.5732	281.3	213.6	131.6
4	0.9301	0.7633	0.5613	275.8	208.4	126.9
5	0.9233	0.7569	0.5559	273.1	205.9	124.6
6	0.9166	0.7507	0.5502	270.4	203.3	122.4
8	0.9032	0.7382	0.5392	265.0	198.3	117.9
10	0.8899	0.7258	0.5284	259.6	193.3	113.5
12	0.8767	0.7136	0.5179	254.3	188.4	109.3
14	0.8635	0.7016	0.5076	248.9	183.5	105.1
15	0.8569	0.6956	0.5025	246.3	181.1	103.1

Table-6(c): Variation of temperature of MTC temperature overlapping (°C) on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H_2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

MTC Temperature overlapping (°C)	Overall system EDR_{LTC}	Overall system EDR_{ITC}	Overall $systemEDR\_{MTC}$	% decrement in EDR_{LTC}	% decrement in EDR_{ITC}	% decrement in EDR_{MTC}
0	0.04859	0.2673	0.7092	98.53	91.21	76.68
2	0.05972	0.2885	0.7447	98.04	90.51	75.51
4	0.07525	0.3101	0.7808	97.53	89.80	74.33
5	0.08302	0.3211	0.7090	97.27	89.44	73.73
6	0.09097	0.3322	0.8174	97.0	89.08	73.12
8	0.1071	0.3547	0.8546	96.48	88.34	71.90
10	0.1237	0.3777	0.8924	95.93	87.58	70.65
12	0.1407	0.4013	0.9310	95.37	86.80	69.39
14	0.1581	0.4254	0.9702	94.80	86.01	68.10
15	0.1669	0.4376	0.9901	94.51	85.61	67.44

3.7 Effect of ecofriendly refrigerants in medium temperature cycle on percentage improvements in total thermodynamic performances of three cascaded cycles in integrated system

System was selected for effect of following ecofriendly refrigerants in MTC systems using NH_3H_2O and R-245fa which has lower GWP than R134a in intermediate temperature cycle at evaporator temperature of -95°C and R32 in ultra-low temperature cycle at evaporator temperature of -130°C. Table-7(a) to Table-7(c) show the comparison between with ecofriendly refrigerants in terms of percentage improvements in thermodynamic performances (First law performances ($COP_{\_Overall}$), second law performance (Exergetic efficiencies) and system exergy destruction Ratios of three cascaded vapour compression refrigeration system coupled with vapour absorption refrigeration NH_3-H_2O system using R245fa ecofriendly refrigerant in intermediate temperature cycle and following ecofriendly refrigerants in medium temperature cycle and R236fa refrigerant in the ultra-low temperature cycle and it is found that the first and second law performances of cascaded vapour compression –vapour-NH_3H_2O absorption system is higher by using HFC-152a ecofriendly refrigerant in medium temperature circuit and R236fa in ultra-low temperature circuit than using HFO-1234yf in MTC cycle.The first law performances using HFO-1234yf, R717 and R134a are nearly approaching similar trend.

Table-7(a): Effect of MTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of integrated NH3-H2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

MTC Refrigerants	Overall system $COP_{\_LTC}$	Overall system $COP_{\_ITC}$	Overall system $COP_{\_MTC}$	% improvement in Overall system $COP_{\_LTC}$	% improvement in Overall system $COP_{\_ITC}$	% improvement in Overall system $COP_{\_MTC}$
R1234yf	0.6443	0.5942	0.4960	100.1	*84.55*	54.05
R152a	0.6535	0.6026	0.5025	102.9	*87.17*	56.06
R717	0.6469	0.5967	0.4979	100.9	*85.31*	54.64
R134a	0.6494	0.5989	0.4996	100.7	*86.0*	55.17

Table-7(b): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of integrated NH3-H2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-134a) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

MTC Refrigerants	Overall system Exergetic Efficiency $_{\_LTC}$	Overall system Exergetic Efficiency $_{ITC}$	Overall system Exergetic Efficiency $_{\_MTC}$	% improvement in Overall system Exergetic Efficiency $_{\_LTC}$	% improvement in Overall system Exergetic Efficiency $_{\_ITC}$	% improvement in Overall system Exergetic Efficiency $_{\_MTC}$
R1234yf	0.8788	0.7156	0.5195	255.1	189.2	109.9
R152a	0.8985	0.7342	0.5367	263.3	196.7	116.5
R717	0.8846	0.7209	0.5242	257.5	191.3	118.8

Table-7(c): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of integrated NH3-H2O VARS multi cascaded VCRS using Low GWP refrigerant (i.e.HFO-1234yf) in medium temperature circuit and GWP refrigerant (i.e.R-245fa) in intermediate temperature circuit and low GWP refrigerant (i.e. R236fa)in ultra low evaporator temperature circuit for low temperature applications

MTC Refrigerants	Overall system $EDR_{\_LTC}$	Overall system $EDR_{\_ITC}$	Overall system $EDR_{\_MTC}$	% decrement in $EDR_{\_LTC}$	% decrement in $EDR_{\_ITC}$	% decrement in $EDR_{\_MTC}$
R1234yf	0.1380	0.3975	0.9248	95.46	86.93	69.59
R152a	0.1124	0.3621	0.8667	96.30	88.09	71.50
R717	0.1304	0.3871	0.9078	95.71	87.27	70.15
R134a	0.1237	0.3777	0.8924	95.93	87.58	70.65

3.8 Effect of ecofriendly refrigerants in medium temperature cycle on percentage improvements in total thermodynamic performances of three cascaded cycles in integrated system

Table-8(a) to Table-8(c) show the comparison between with ecofriendly refrigerants in terms of percentage improvements in thermodynamic performances (First law performances ($COP_{\_Overall}$), second law performance (Exergetic efficiencies) and system exergy destruction Ratios of three cascaded vapour compression refrigeration system coupled with vapour absorption refrigeration NH_3-H_2O system using R245fa ecofriendly refrigerant in intermediate temperature cycle and following ecofriendly refrigerants in medium temperature cycle and R236fa refrigerant in the ultra low temperature cycle and it is found that the first and second law performances of cascaded vapour compression –vapour-NH_3H_2O absorption system is higher by using HFC-152a ecofriendly refrigerant in medium temperature circuit and R236fa in ultra low temperature circuit than using HFO-1234yf im MTC cycle.The first law performances using HFO-1234yf, R717 and R134a are nearly approaching similar trend.

Table-8(a): Effect of MTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of Integrated NH_3-H_2O VARS multi cascaded VCRS using following ecofriendly refrigerants in medium temperature circuit of evaporator temperature of -50°C and R-134a in intermediate temperature circuit of evaporator temperature of -95°C and R-32 in intermediate temperature circuit of evaporator temperature of -130°C in systems for ultra low temperature applications

MTC Refrigerants	Overall system COP_LTC	Overall system COP_ITC	Overall system COP_MTC	% improvement in Overall system COP_LTC	% improvement in Overall system COP_ITC	% improvement in Overall system COP_MTC
R1234yf	0.6434	0.5942	0.4960	99.84	*84.34*	54.05
R152a	0.6526	0.6026	0.5025	102.7	*86.95*	56.06
R717	0.6461	0.5967	0.4979	100.7	*85.10*	44.79
R245fa	0.6515	0.6009	0.5017	102.3	*86.64*	55.82

Table-8(b): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of Integrated NH_3-H_2O VARS multi cascaded VCRS using following ecofriendly refrigerants in medium temperature circuit of evaporator temperature of -50°C and R-134a in intermediate temperature circuit of evaporator temperature of -95°C and R-32 in intermediate temperature circuit of evaporator temperature of -130°C in systems for ultra low temperature applications

MTC Refrigerants	Overall system Exergetic Efficiency _LTC	Overall system Exergetic Efficiency ITC	Overall system Exergetic Efficiency _MTC	% improvement in Overall system Exergetic Efficiency _LTC	% improvement in Overall system Exergetic Efficiency _ITC	% improvement in Overall system Exergetic Efficiency _MTC
R1234yf	0.8763	0.7134	0.5195	254.1	188.3	109.9
R152a	0.8963	0.7319	0.5367	262.2	195.8	116.5
R717	0.8821	0.7188	0.5242	256.5	190.5	118.8
R134a	0.8939	0.7297	0.5337	261.2	194.9	115.7

Table-8(c): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of Integrated NH_3-H_2O VARS multi cascaded VCRS using following ecofriendly refrigerants in medium temperature circuit of evaporator temperature of -50°C and R-134a in intermediate temperature circuit of evaporator temperature of -95°C and R-32 in intermediate temperature circuit of evaporator temperature of -130°C in systems for ultra-low temperature applications

MTC Refrigerants	Overall system EDR_LTC	Overall system EDR_ITC	Overall system EDR_MTC	% decrement in EDR_LTC	% decrement in EDR_ITC	% decrement in EDR_MTC
R1234yf	0.1412	0.4017	0.9248	95.36	86.93	69.59
R152a	0.1516	0.3662	0.8667	96.20	88.09	71.50
R717	0.1337	0.3913	0.9078	95.60	87.27	70.15
R134a	0.1187	0.3704	0.8736	96.1	87.58	71.27

3.9 Comparison of various integrated cascaded vapour compression-absorption systems

Three Integrated vapour compression-absorption refrigeration systems were compared for finding the effect of following ecofriendly refrigerants in LTC systems at evaporator temperature of -130°C using NH_3H_2O VARS and R-245fa which has lower GWP than R134a in intermediate temperature cycle at evaporator temperature of -95°C (system-1) and also comparing with R32 used in ITC shown in table-10(a) to table—10(c) and also R134a in intermediate temperature cycle at evaporator temperature of -95°C and following ecofriendly refrigerants at -130°C (system-3) for ultra-low temperature applications shown in table-11(a) to Table-11(c) respectively. It was observed that system-2 gives lowest thermodynamic performances in terms of first and second low efficiency with higher exergy destruction rate. However the system-1 consisting of NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50°C and R-245fa in intermediate temperature circuit of evaporator temperature of -95°C following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130°C gives better thermodynamic performances than system-3 consisting of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50°C and R-134a in intermediate temperature circuit of evaporator temperature of -95°C following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130°C.It was found that R236fa and Hydro carbon 600a gives similar thermodynamic performance first and second law performances in terms of COPs and exergetic efficiencies as shown in table-9(a) to Table-11(c) respectively for all three systems.

Table-9(a): Effect of LTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-245fa in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130ºC (System-1)

LTC Refrigerants	Overall system COP_LTC	Overall system COP_ITC	Overall system COP_MTC	% improvement in Overall system COP_LTC	% improvement in Overall system COP_ITC	% improvement in Overall system COP_MTC
R236fa	0.6206	0.5942	0.4960	92.74	*84.55*	54.05
R290	0.6180	0.5942	0.4960	91.95	*84.55*	54.05
R600a	0.6205	0.5942	0.4960	92.71	*84.55*	54.05
Ethylene	0.6154	0.5942	0.4960	91.12	*84.55*	54.05
R410a	0.6136	0.5942	0.4960	91.58	*84.55*	54.05
R404a	0.6171	0.5942	0.4960	91.65	*84.55*	54.05

Table-9(b): Effect of LTC refrigerants on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-245fa in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130ºC(System-1)

LTC Refrigerants	Overall system Exergetic Efficiency _LTC	Overall system Exergetic Efficiency ITC	Overall system Exergetic Efficiency _MTC	% improvement in Overall system Exergetic Efficiency _LTC	% improvement in Overall system Exergetic Efficiency _ITC	% improvement in Overall systemExergetic Efficiency _MTC
R236fa	0.8559	0.7156	0.5195	245.9	189.2	109.9
R290	0.8555	0.7156	0.5195	241.4	189.2	109.9
R600a	0.8555	0.7156	0.5195	245.7	189.2	109.9
Ethylene	0.8333	0.7156	0.5195	236.7	189.2	109.9
R410a	0.8250	0.7156	0.5195	233.7	189.2	109.9
R404a	0.8409	0.7156	0.5195	239.7	189.2	109.9

Table-9(c): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-245fa in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130ºC(System-1)

LTC Refrigerants	Overall system EDR_LTC	Overall system EDR_ITC	Overall system EDR_MTC	% decrement in EDR_LTC	% decrement in EDR_ITC	% decrement in EDR_MTC
R236fa	0.1684	0.3975	0.9248	94.46	86.93	69.59
R290	0.1838	0.3975	0.9248	93.96	86.93	69.59
R600a	0.1689	0.3975	0.9248	94.45	86.93	69.59
Ethylene	0.201	0.3975	0.9248	93.42	86.93	69.59
R410a	0.2109	0.3975	0.9248	93.46	86.93	69.59
R404a	0.1896	0.3975	0.9248	93.76	86.93	69.59

Table-10(a): Effect of MTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-32 in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra low temperature applications of evaporator temperature of -130ºC (System-2)

LTC Refrigerants	Overall system COP_LTC	Overall system COP_ITC	Overall system COP_MTC	% improvement in Overall system COP_LTC	% improvement in Overall system COP_ITC	% improvement in Overall system COP_MTC
R236fa	0.6141	0.5882	0.4960	88.68	*82.68*	54.05
R290	0.6116	0.5882	0.4960	89.95	*82.68*	54.05
R600a	0.6140	0.5882	0.4960	90.70	*82.68*	54.05
Ethylene	0.6091	0.5882	0.4960	89.16	*82.68*	54.05
R410a	0.6074	0.5882	0.4960	88.68	*82.68*	54.05
R404a	0.6107	0.5882	0.4960	89.67	*82.68*	54.05

Table-10(b): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. exergetic efficiency) and percentage improvement of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-32 in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130ºC (System-2)

LTC Refrigerants	Overall system Exergetic Efficiency _LTC	Overall system Exergetic Efficiency ITC	Overall system Exergetic Efficiency _MTC	% improvement in Overall system Exergetic Efficiency _LTC	% improvement in Overall system Exergetic Efficiency _ITC	% improvement in Overall system Exergetic Efficiency _MTC
R236fa	0.8069	0.6969	0.5195	237.7	181.6	109.9
R290	0.8250	0.6969	0.5195	233.4	181.6	109.9
R600a	0.8353	0.6969	0.5195	237.5	181.6	109.9
Ethylene	0.8140	0.6969	0.5195	229.0	181.6	109.9
R410a	0.8069	0.6969	0.5195	226.1	181.6	109.9
R404a	0.8211	0.6969	0.5195	231.8	181.6	109.9

Table-10(c): Effect of MTC refrigerants on thermodynamic second law performance parameter (i.e. Exergy destruction ratio) and decrement in EDRs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-32 in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra low temperature applications of evaporator temperature of -130ºC (System-2)

LTC Refrigerants	Overall system EDR_LTC	Overall system EDR_ITC	Overall system EDR_MTC	% decrement in EDR_LTC	% decrement in EDR_ITC	% decrement in EDR_MTC
R236fa	0.1966	0.4348	0.9248	9354	85.7	69.59
R290	0.2121	0.4348	0.9248	93.03	85.7	69.59
R600a	0.1992	0.4348	0.9248	93.52	85.7	69.59
Ethylene	0.2284	0.4348	0.9248	92.49	85.7	69.59
R410a	0.2393	0.4348	0.9248	92.13	85.7	69.59
R404a	0.2179	0.4348	0.9248	92.83	85.7	69.59

*Table-11(a): Effect of LTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and **R-134a** in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra low temperature applications of evaporator temperature of -130ºC (System-3)*

LTC Refrigerants	Overall system COP_LTC	Overall system COP_ITC	Overall system COP_MTC	% improvement in Overall system COP_LTC	% improvement in Overall system COP_ITC	% improvement in Overall system COP_MTC
R236fa	0.6199	0.5935	0.4960	92.51	*84.34*	54.05
R290	0.6173	0.5935	0.4960	91.71	*84.34*	54.05
R600a	0.6198	0.5935	0.4960	92.48	*84.34*	54.05
Ethylene	0.6147	0.5935	0.4960	91.90	*84.34*	54.05
R410a	0.6129	0.5935	0.4960	91.36	*84.34*	54.05
R404a	0.6163	0.5935	0.4960	91.42	*84.34*	54.05
R407c	0.5918	0.5935	0.4960	83.81	*84.34*	54.05

Table-11(b): Effect of MTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50ºC and R-134a in intermediate temperature circuit of evaporator temperature of -95ºC following ecofriendly refrigerants in systems for ultra low temperature applications of evaporator temperature of -130ºC(System-3)

LTC Refrigerants	Overall system Exergetic Efficiency _LTC	Overall system Exergetic Efficiency ITC	Overall system Exergetic Efficiency _MTC	% improvement in Overall system Exergetic Efficiency _LTC	% improvement in Overall system Exergetic Efficiency _ITC	% improvement in Overall system Exergetic Efficiency _MTC
R236fa	0.8559	0.7134	0.5195	244.9	188.3	109.9
R290	0.8555	0.7134	0.5195	240.5	188.3	109.9
R600a	0.8555	0.7134	0.5195	244.8	188.3	109.9
Ethylene	0.8333	0.7134	0.5195	235.8	188.3	109.9
R410a	0.8250	0.7134	0.5195	232.8	188.3	109.9
R404a	0.8409	0.7134	0.5195	238.8	188.3	109.9
R407c	0.7537	0.7134	0.5195	197.3	188.3	109.9

Table-11(c): Effect of MTC refrigerants on thermodynamic on thermodynamic first law performance parameter (i.e. coefficient of performance) and percentage improvement in COPs of Integrated NH_3-H_2O VARS multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50°C and R-134a in intermediate temperature circuit of evaporator temperature of -95°C following ecofriendly refrigerants in systems for ultra low temperature applications of evaporator temperature of -130°C (System-3)

LTC Refrigerants	Overall system EDR_{LTC}	Overall system EDR_{ITC}	Overall system EDR_{MTC}	% decrement in EDR_{LTC}	% decrement in EDR_{ITC}	% decrement in EDR_{MTC}
R236fa	0.1715	0.4017	0.9248	94.36	86.79	69.59
R290	0.1810	0.4017	0.9248	93.85	86.79	69.59
R600a	0.1721	0.4017	0.9248	94.34	86.79	69.59
Ethylene	0.2033	0.4017	0.9248	93.32	86.79	69.59
R410a	0.2141	0.4017	0.9248	93.96	86.79	69.59
R404a	0.1928	0.4017	0.9248	93.66	86.79	69.59
R407c	0.3592	0.4017	0.9248	88.19	86.79	69.59

4. Conclusions

For replacing R134a due to high global warming potential as compared to HFO refrigerants and natural refrigerants, following conclusions were drawn from present investigations.

- System-1 containing NH_3H_2O vapour absorption refrigeration system cascaded with three vapour compression refrigeration cycles containing HFO-1234yf refrigerant in cascaded medium temperature cycle and R245fa used in intermediate temperature cycle and R236fa in ultra-low temperature cycle is suitable for replacing R134a in intermediate temperature cycle due to better thermodynamic performances and lower exergy destruction ratio.
- As LTC evaporator temperature is increasing from (-135°C to -120°C), the first law efficiency (COP_overall system) of integrated vapour compression absorption system is increasing while and second law efficiency (exergetic efficiency) of cascaded vapour compression NH_3H_2O vapour absorption refrigeration system is increasing in all three integrated multi cascaded vapour compression-absorption refrigeration systems
- ITC evaporator temperature is increasing from (-95°C to -75°C), the first law efficiency (COP_overall system) of integrated vapour compression absorption system is increasing while and second law efficiency (exergetic efficiency) of cascaded vapour compression NH_3H_2O vapour absorption refrigeration system is increasing in all three integrated multi cascaded vapour compression-absorption refrigeration systems
- used in ITC for ultra-low evaporator temperature applications.
- System-3 containing NH_3H_2O vapour absorption system multi cascaded VCRS using HFO-1234yf in medium temperature circuit of evaporator temperature of -50°C and
- The first law efficiency (COP_system) of combined NH_3H_2O vapour absorption compression and three cascading VCR system is increasing while and second law efficiency (exergetic efficiency) of cascaded vapour compression combined NH_3H_2O vapour absorption refrigeration system is increasing as medium evaporator temperature using HFO-1234yf is increasing in all three integrated multi cascaded vapour compression-absorption refrigeration systems. Similarly exergy destruction ratio based on exergy of product is also decreasing as medium evaporator temperature circuit temperature using HFO-1234yf eco-friendly refrigerant is decreasing.
- As temperature overlapping is increasing, the first law efficiency (COP) and second law efficiency (exergetic efficiency) of cascaded compression- Absorption systems are decreasing as temperature overlapping is increasing. Similarly exergy destruction ratio based on exergy of product is also decreasing as temperature overlapping (approach) is increasing.
- In the Combined vapour compression –NH_3H_2O absorption refrigeration systems, the first and second law performances by using HFC-152a ecofriendly refrigerant in medium temperature circuit and R236fa in ultra low temperature circuit is higher than using HFO-1234yf in MTC cycle at -50°C .
- In the cascaded vapour compression –vapour-NH_3H_2O absorption system, R-245fa which has lower GWP than R134a in intermediate temperature cycle at evaporator temperature of -95°C (system-1) is better than using R134a R-32 in intermediate temperature circuit of evaporator temperature of -95°C following ecofriendly refrigerants in systems for ultra-low temperature applications of evaporator temperature of -130°C gives lower thermodynamic performances.

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