



ORIGINAL ARTICLE

Performance evaluation of single effect Li/Br-H₂O vapour absorption refrigeration system with three cascaded vapour compression refrigeration systems using HFO refrigerants for ultra-low temperature applications

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Abstract

The potential alternative absorption refrigeration technology is due to the utilization of renewable and nonrenewable energy resources through vapour compression-absorption refrigeration systems for ultra-low temperature applications. The main issues observed with the vapour absorption refrigeration systems are low overall COP and large size of system which is mainly due to the reduced thermodynamic performance.

This paper mainly deals with the utility of HFO refrigerants in cascaded vapour compression cycles for low temperature and ultra-low temperature applications using single effect Li/Br-H₂O absorption unit. The percentage improvement in overall first law (energy) performance of cascaded system is 7.88% to 8.67% using R1233zd(E), 3.36% to 4.15% by using R1225ye(Z) and 4.66% to 5.45% using HFO-1336mzz(Z) by increasing the generator temperature from 90oC to 120oC, and percentage improvement in exergetic efficiency, from 26.1% to 55.67% by using R1233zd(E) and 17.43% to 45.5 % by using R1225ye(Z) and 17.4% to 45.49% by using HFO-1336mzz(Z) for low evaporator temperature of -65oC respectively. However, the performances decrease by increasing condenser and absorber temperatures.

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1. Introduction

For reducing global warming and ozone depletion and maximizing the use of natural and renewable energy resources with minimal environmental impacts is key building of an energy efficient sustainable system. Although completely sustainable energy efficient system would require a fully reversible process, exploits the second law of thermodynamics which proves is not possible, which indicating that all real processes are irreversible and impact on the environment. Approaching sustainability can yield greater benefits both the current and future environment. The utilization of natural and

renewable resources in a responsible fashion and by using efficient methods is important aspect when developing new technologies and analyzing current refrigeration and air conditioning systems. The conventional vapour compression refrigeration systems and vapour absorption systems utilize different working fluids. Many of the vapour compression systems use the ozone depleting chloro-fluoro-carbon refrigerants (CFCs), Hydro-chloro-fluoro-carbon refrigerants (HCFCs), Hydro-fluoro-carbon refrigerants (CFCs), because of the thermo-physical properties obtainable by them. Many industrial processes frequently produce a significant amount of thermal energy; regularly by burning fossil fuels for heat or

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steam. The opportunities to convert wastes or excess heat into useful cooling can be done by integration of absorption refrigeration systems into these systems. Szargut et al [1]. suggested that exergy methods should be considered to better realize increased efficiencies and environmental impacts because exergy is normally considered to be the measure of work potential (i.e. maximum work) that can be obtained from a system with respect to its environment. The exergy, is a non-conserved quantity, and exergy balances account for inputs, losses and wastes of a process. the exergy input and destruction rates provide an accounting of the utilized efficiency of resources used. Rosen and Dincer [2] have given links between energy, exergy and sustainable development, which shows that exergy may allow for measuring impacts on the environment Gebreslassie et al [3] had evaluated exergy in Lithium bromide (Li/Br) absorption systems by using structural method to obtain a simplified equation to estimate the optimum heat exchanger area for absorption cooling system and assessed the relationship between heat exchange area and exergy. Also concluded that in the optimum case, the maximum exergy destruction was in the solution heat exchanger and the condenser while in all other components, the destruction rates decreasing as increased heat exchange area and presented at detailed analysis of exergy for half to triple effect absorption chillers. Bereche et al [4] analyzed single and double-effect LiBr systems using a thermo-economic analysis and exergy and concluded that the single-effect absorption refrigeration systems are suitable utilizing waste heat or operating in cogeneration systems because of their operation at lower temperatures compared to double-effect chillers, Morosuk and Tsatsaron [5] is presented an exergy analysis of the internal components of absorption refrigeration machines. And concluded that the absorber and generator destroyed about 40% of their exergy and are main (primary) candidates for improvement. Kilic and Kaynakli [6] carried out a second law(exergy) thermodynamic analysis of water and lithium bromide absorption refrigeration and found the evaporator is a major component for the exergy loss rates and concluded that the generator, absorber and evaporator were the largest sources of exergy destruction. Garimella et al [7] proposed absorption/vapour compression cascade refrigeration system driven by waste heat used in naval ship and concluded that electricity consumption is reduced by 31% than that of conventional vapour compression refrigeration system. The large number of research studies on cascade refrigeration systems have been done. These research studies provide valuable insights about energy and exergy analysis of VCR, VAR cycles in the single, double and triple stage and compression-absorption in the form of cascade cycles. Most of the research studies considered till date emphasize on VCR and VAR cycles (single and double effect, triple and half effect in Li/Br-H₂O and NH₃H₂O). Mishra [8] carried out exergy- energy analysis of compression-absorption (combined) or cascade cycles. Though, exhaustive research has been carried out on cascade cycles, but very less consideration has been given to explore the thermodynamic performance using HFO refrigerants in the

range from -30°C to -150°C and none of the research work is available on performance analysis of compression-absorption cascade refrigeration system using HFO refrigerants. Radhey Shyam Mishra [9-10] carried out thermodynamic performance of the HFO refrigerants in the medium temperature compression stage between 5°C to -50°C and NH₃H₂O, Li/Br-H₂O refrigerants in the absorption stage and its overall effect on the cascade system. The effect of these HFO refrigerants on the intermediate temperature in the range of (-50°C to 95°C) using R245fa of medium temperature cycle cascade system using R32 refrigerant/ hydrocarbons in ultra-low evaporator temperature first and second law performances using the pair of NH₃-H₂O in the high temperature absorption stage and HFO refrigerants at the evaporator temperature of 223K (-50°C) and R245fa in the medium temperature compression cycle for evaporator temperature of -95°C evaluated the effect of various performance parameters of multi cascade refrigeration system in which a compression system at the low temperature stage using R32 in low temperature cycle at evaporator temperature of -130°C. It is found that R1233zd (E), R1225ye(Z) and HFO-1336mzz(z) gives better thermodynamic performances than using R1243yf. The studies carried out so far on the double and triple effect cycles in the use of HFO refrigerants up to evaporator temperature of -50°C in cascaded vapour compression refrigeration systems. to some extent, the effect of HFO refrigerants in the intermediate temperature cycle at -75°C and -95°C is missing. Also the effect of HFO –refrigerants in ultra-low temperature cycle of compression –absorption refrigeration systems have not been investigated so far. The present study has therefore been carried out the effect of HFO refrigerants in intermediate temperature cycle(ITC) up to -95°C and LTC evaporator of -135°C and -150°C.

2. Results and Discussion

Following systems have been taken for performance evaluations.

System-1

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature = -50°C, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -150°C.

System-2

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature = -50°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using R-1225ye(Z) in lower

temperature cycle at evaporator temperature = -150°C.

System-3

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf in medium temperature cycle at evaporator temperature = -50°C, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -150°C.

System-4

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf) in medium temperature cycle at evaporator temperature = -50°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -150°C. Following numerical values have been used for validation of code developed for Integrated single effect Li/Br-H₂O VARS using ecofriendly refrigerants.

- Generator temperature= 110°C

- Absorber temperature=35°C
- Condenser temperature =35°C
- VARS evaporator temperature=10°C
- load on VARS Evaporator= 175 kW
- Ambient (dead state) temperature=25°C
- Temperature overlapping in MTC = 10°C
- VCR evaporator temperature of MTC=-50°C
- VCR evaporator temperature of ITC=-95°C
- VCR evaporator temperature of LTC=-150°C
- VCR compressor efficiency of MTC= 80%
- VCR compressor efficiency of ITC= 80%
- VCR compressor efficiency of LTC= 80%
- Ambient (dead state) temperature=25°C

Thermodynamic first law energy performances of integrated single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems shown in table 2(a) respectively. It was observed that system-6 has lowest thermodynamic performances than system-5, however first law thermodynamic performance improvement is less. Similarly, Thermodynamic second law exergy performances of cascaded single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems shown in table-2(b) respectively. It was observed that system-6 has higher thermodynamic exergetic performances than system-5.

Table-1(a) Thermodynamic first law (energetic) Performances of Integrated single effect Li/Br-H₂O VARS using ecofriendly refrigerants at evaporator temperature=-150°C

| Integrate system | COP_VARS | COP_MTC | COP_ITC | COP_LTC | % Improvement in COP_MTC | % Improvement in COP_ITC | % Improvement in COP_LTC |
|------------------|----------|---------|---------|---------|--------------------------|--------------------------|--------------------------|
| System-1 | 0.7560 | 0.8759 | 0.9847 | 0.9236 | 15.86 | 30.65 | 22.17 |
| System-2 | 0.7560 | 0.8759 | 0.9847 | 0.9282 | 15.86 | 30.26 | 22.79 |
| System-3 | 0.7560 | 0.8102 | 0.9120 | 0.8634 | 7.168 | 20.64 | 14.22 |
| System-4 | 0.7560 | 0.8102 | 0.9120 | 0.8674 | 7.168 | 20.31 | 14.74 |

Table-1(b) Thermodynamic second law (exergetic) Performances of Integrated single effect Li/Br-H₂O VARS using ecofriendly refrigerants at evaporator temperature=-150°C

| Integrate system | ETA_VARS | ETA_MTC | ETA_ITC | ETA_LTC | % Improvement in ETA_MTC | % Improvement in ETA_ITC | % Improvement in ETA_LTC |
|------------------|----------|---------|---------|---------|--------------------------|--------------------------|--------------------------|
| System-1 | 0.1564 | 0.321 | 0.5331 | 0.5539 | 77.98 | 195.3 | 206.8 |
| System-2 | 0.1564 | 0.321 | 0.5293 | 0.5639 | 77.98 | 193.1 | 212.3 |
| System-3 | 0.1564 | 0.2680 | 0.4561 | 0.4890 | 48.94 | 152.6 | 170.9 |
| System-4 | 0.1564 | 0.2689 | 0.4530 | 0.4974 | 48.94 | 150.9 | 175.5 |

Table-1(c) Thermodynamic exergy destruction ratio of Integrated single effect Li/Br-H₂O VARS using ecofriendly refrigerants at evaporator temperature= -150°C

| Integrate system | EDR_VARS | EDR_MTC | EDR_ITC | EDR_LTC | % Improvement in EDR_MTC | % Improvement in EDR_ITC | % Improvement in EDR_LTC |
|------------------|----------|---------|---------|---------|--------------------------|--------------------------|--------------------------|
| System-1 | 4.539 | 2.112 | 0.8754 | 0.8053 | -53.47 | -80.7 | -82.26 |
| System-2 | 4.539 | 2.112 | 0.8894 | 0.7735 | -53.47 | -80.4 | -82.96 |
| System-3 | 4.539 | 2.719 | 0.8754 | 0.8053 | -40.10 | -73.72 | -76.98 |
| System-4 | 4.539 | 2.719 | 0.8754 | 0.8053 | 40.10 | -73.40 | -77.74 |

However, second law thermodynamic exergetic performance

improvement for -150°C evaporator temperature is less. It means

by putting HFO-1336mzz(Z) in lower temperature cycle in system-5 gives lower first and second law thermodynamic performances than using R-1225ye(Z) in low temperature cycle. However, first law(energy) and second law exegetic performances of double stage cascaded integrated system-5 is higher than double stage cascaded integrated system-6 at evaporator temperature of -95°C. It means by putting HFO-1336mzz(Z) in intermediate temperature cycle gives lower first and second law thermodynamic performances than using R-1225ye(Z). The exergy destruction ratio of whole cascaded system is shown in Table-2(c) respectively.

System-5

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234ze(Z) in medium temperature cycle at evaporator temperature = -30°C, R1225ye(Z) in intermediate temperature cycle at evaporator temperature = -75°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-6

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234ze(Z) in medium temperature cycle at evaporator temperature = -30°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -75°C and using R1225ye(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-7

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234ze(E) in medium temperature cycle at evaporator temperature = -30°C, R1225ye(Z) in intermediate temperature cycle at evaporator temperature = -75°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-8

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234ze(E) in medium temperature cycle at evaporator temperature = -30°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -75°C and using R1225ye(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-9

Li/Br-H₂O single effect vapour absorption refrigeration system

at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1243zf in medium temperature cycle at evaporator temperature = -50°C, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-10

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1243zf in medium temperature cycle at evaporator temperature = -30°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -75°C and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-11

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature = -50°C, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-12

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature = -50°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -150°C.

System-13

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf in medium temperature cycle at evaporator temperature = -50°C, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135°C.

System14

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf in medium temperature cycle at evaporator temperature = -50°C, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95°C and using R-1225ye(Z) in lower

temperature cycle at evaporator temperature = -135°C.

System-15

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R-1225ye(Z) in medium temperature cycle at evaporator temperature = -50°C, R1233zd(E) in intermediate temperature cycle at evaporator temperature = -95°C and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135°C.

System-16

Li/Br-H₂O single effect vapour absorption refrigeration system at 10°C of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf in medium temperature cycle at evaporator temperature = -50°C, R1233zd(E) in intermediate temperature cycle at evaporator temperature = -95°C and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135°C.

Following numerical values have been used for validation of code developed for Integrated single effect Li/Br-H₂O VARS

using ecofriendly refrigerants

- Generator temperature= 110°C
- Absorber temperature=35°C
- Condenser temperature =35°C
- VARS evaporator temperature=10°C
- load on VARS Evaporator= 175 kW
- Ambient (dead state) temperature=25°C
- Temperature overlapping in MTC = 10°C
- VCR evaporator temperature of MTC=-30°C
- VCR evaporator temperature of ITC=-75°C
- VCR evaporator temperature of LTC=-135°C
- VCR compressor efficiency of MTC= 80%
- VCR compressor efficiency of ITC= 80%
- VCR compressor efficiency of LTC= 80%
- Ambient (dead state) temperature=25°C

Thermodynamic first law energy performances of integrated single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems shown in table 2(a) respectively. It was observed that system-2 has lowest thermodynamic performances than system-1, however first law thermodynamic performance improvement is less

Table-2(a) Thermodynamic first law (energetic) Performances of Integrated single effect Li/Br-H₂O VARS using ecofriendly refrigerants at evaporator temperature=-135°C

| Integrate system | COP_VARS | COP_MTC | COP_ITC | COP_LTC | %Improvement in COP_MTC | %Improvement in COP_ITC | % Improvement in COP_LTC |
|------------------|----------|---------|---------|---------|-------------------------|-------------------------|--------------------------|
| System-5 | 0.7560 | 1.002 | 1.145 | 1.05 | 32.56 | 51.44 | 38.96 |
| System-6 | 0.7560 | 1.002 | 1.143 | 1.057 | 32.58 | 51.15 | 39.82 |
| System-7 | 0.7560 | 0.9662 | 1.104 | 1.020 | 27.81 | 46.032 | 34.92 |
| System-8 | 0.7560 | 0.9662 | 1.102 | 1.057 | 27.81 | 45.82 | 35.75 |
| System-9 | 0.7560 | 0.9698 | 1.108 | 1.057 | 28.29 | 46.62 | 35.35 |
| System-10 | 0.7560 | 0.9698 | 1.106 | 1.057 | 28.29 | 46.36 | 36.16 |
| System-11 | 0.7560 | 0.9961 | 1.138 | 1.057 | 31.76 | 50.53 | 38.28 |
| System-12 | 0.7560 | 0.9961 | 1.138 | 1.045 | 31.76 | 50.53 | 38.28 |
| System-13 | 0.7560 | 0.9431 | 1.078 | 1.0 | 24.76 | 42.62 | 32.31 |
| System-14 | 0.7560 | 0.9431 | 1.076 | 1.006 | 24.76 | 42.37 | 32.08 |
| System-15 | 0.7560 | 0.9634 | 1.102 | 1.018 | 27.44 | 45.74 | 34.68 |
| System-16 | 0.7560 | 0.9794 | 1.120 | 1.039 | 29.56 | 48.13 | 37.5 |

Table-2(b) Thermodynamic second law (exergetic) Performances of Integrated single effect Li/Br-H₂O VARS using ecofriendly refrigerants at evaporator temperature=-135°C

| Integrate system | ETA_VARS | ETA_MTC | ETA_ITC | ETA_LTC | %Improvement in ETA_MTC | % Improvement in ETA_ITC | %Improvement in ETA_LTC |
|------------------|----------|---------|---------|---------|-------------------------|--------------------------|-------------------------|
| System-5 | 0.1560 | 0.322 | 0.5278 | 0.5383 | 78.49 | 192.3 | 198.1 |
| System-6 | 0.1560 | 0.3223 | 0.5255 | 0.5491 | 78.49 | 191.0 | 204.1 |
| System-7 | 0.1560 | 0.2970 | 0.4936 | 0.5126 | 64.50 | 173.5 | 183.5 |
| System-8 | 0.1560 | 0.2970 | 0.4917 | 0.5227 | 64.5 | 172.3 | 189.5 |
| System-9 | 0.1560 | 0.2992 | 0.4972 | 0.5152 | 65.86 | 175.4 | 185.3 |
| System-10 | 0.1560 | 0.2995 | 0.4951 | 0.5253 | 65.86 | 174.5 | 191.0 |
| System-11 | 0.1560 | 0.3170 | 0.5219 | 0.5339 | 76.04 | 189.1 | 195.7 |
| System-12 | 0.1560 | 0.3170 | 0.5219 | 0.5339 | 76.04 | 189.1 | 195.7 |
| System-13 | 0.1560 | 0.2817 | 0.4723 | 0.4958 | 55.96 | 161.6 | 174.6 |
| System-14 | 0.1560 | 0.2816 | 0.4704 | 0.5054 | 55.96 | 160.5 | 179.9 |
| System-15 | 0.1560 | 0.2950 | 0.4918 | 0.5110 | 55.96 | 172.4 | 183.0 |
| System-16 | 0.1560 | 0.3061 | 0.5068 | 0.5347 | 69.54 | 180.7 | 196.1 |

Table-2(c) Thermodynamic exergy destruction ratio of Integrated single effect Li/Br-H₂O VARS at evaporator temperature=-135°C

| Integrate system | EDR_VARS | EDR_MTC | EDR_ITC | ED R_LTC | % Improve in EDR_MTC | %Improvement in EDR_ITC | %Improvement in EDR_LTC |
|------------------|----------|---------|---------|----------|----------------------|-------------------------|-------------------------|
| System-5 | 4.539 | 2.103 | 0.9031 | 0.8212 | -53.66 | -80.10 | -81.91 |
| System-6 | 4.539 | 2.103 | 0.8947 | 0.8577 | -53.66 | -80.29 | -81.1 |
| System-7 | 4.539 | 2.367 | 1.025 | 0.9529 | -47.85 | -77.41 | -79.05 |
| System-8 | 4.539 | 2.367 | 1.034 | 0.9133 | -47.82 | -77.23 | -79.88 |
| System-9 | 4.539 | 2.339 | 1.011 | 0.9410 | -48.46 | -77.72 | -79.23 |
| System-10 | 4.539 | 2.339 | 1.02 | 0.9036 | -48.46 | -77.53 | -80.09 |
| System-11 | 4.539 | 2.146 | 0.916 | 0.8729 | -52.71 | -79.82 | -80.77 |
| System-12 | 4.539 | 2.146 | 0.916 | 0.8729 | -52.71 | -79.82 | -80.77 |
| System-13 | 4.539 | 2.551 | 1.117 | 1.017 | -43.79 | -75.39 | -77.6 |
| System-14 | 4.539 | 2.551 | 1.126 | 0.9785 | -47.37 | -77.23 | -78.92 |
| System-15 | 4.389 | 2.551 | 1.033 | 0.9569 | -43.79 | -75.19 | -78.44 |
| System-16 | 4.539 | 2.267 | 0.9730 | 0.8703 | -50.06 | -78.56 | -80.83 |

Similarly, Thermodynamic second law exergy performances of cascaded single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems shown in table-2(b) respectively. It was observed that system-2 has higher thermodynamic exergetic performances than system-1. However, second law thermodynamic exergetic performance improvement for -150°C evaporator temperature is less. It means by putting HFO-1336mzz(Z) in lower temperature cycle in system-1 gives lower first and second law thermodynamic performances than using R-1225ye(Z) in low temperature cycle. However, first law(energy) and second law exergetic performances of double stage cascaded integrated system-1 is higher than double stage cascaded integrated system-2 at evaporator temperature of -95°C. It means by putting HFO-1336mzz(Z) in intermediate temperature cycle gives lower first and second law thermodynamic performances than using R-

1225ye(Z). The exergy destruction ratio of whole cascaded system is shown in Table-2(c) respectively. Thermodynamic first law energy performances of integrated single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems with varying evaporator temperature is shown in table -3 respectively. It was observed that by increasing VAR evaporator temperature, the thermodynamic first law (energy) performance is increases while second law (exergy)efficiency is decreases and exergy destruction ratio is increases. Similarly, Thermodynamic second law exergy performances of cascaded single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems with variation of absorber temperature is shown in table-4 respectively. It was observed thermodynamic performances is decreases, by increasing absorber temperature.

Table-3 Thermodynamic (exergy) performances of Integrated single effect Li/Br-H₂O VARS using R1233zd(E) ecofriendly refrigerants at MTC evaporator temperature=-65°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Evaporator temperature of VARS (°C) | COP_VARS | EDR | Exergetic Efficiency | COP_cascade | EDR_cascade | Exergetic Efficiency_cascade | % Improvement in COP_cascade | % Decrement in EDR_cascade | %Improv-ment in Exergetic Efficiency_cascade |
|-------------------------------------|----------|-------|----------------------|-------------|-------------|------------------------------|------------------------------|----------------------------|--|
| 3 | 0.7360 | 2.783 | 0.2643 | 0.7789 | 1.933 | 0.3410 | 5.03 | -30.56 | 29.0 |
| 4 | 0.7410 | 2.964 | 0.2523 | 0.7808 | 1.970 | 0.3367 | 5.03 | -33.55 | 33.48 |
| 5 | 0.7560 | 3.163 | 0.2402 | 0.7827 | 2.008 | 0.3325 | 5.03 | -36.52 | 38.41 |
| 6 | 0.7438 | 3.382 | 0.2282 | 0.7848 | 2.046 | 0.3283 | 5.03 | -39.49 | 43.84 |
| 7 | 0.7466 | 3.624 | 0.2163 | 0.7869 | 2.085 | 0.3241 | 5.03 | -42.46 | 49.87 |
| 8 | 0.7496 | 3.894 | 0.2043 | 0.7892 | 2.125 | 0.320 | 5.03 | -45.42 | 56.60 |
| 9 | 0.7525 | 4.197 | 0.1924 | 0.7916 | 2.166 | 0.3159 | 5.16 | -48.40 | 64.16 |
| 10 | 0.7560 | 4.539 | 0.1805 | 0.7940 | 2.207 | 0.3119 | 5.03 | -51.38 | 72.73 |

Table-4 Effect of Absorber temperature on thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1233zd(E) ecofriendly refrigerants at MTC evaporator temperature=-65°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Absorber temperature of VARS (°C) | COP_VARS | EDR | Exergetic Efficiency | COP_cascade | EDR_cascade | Exergetic Efficiency_cascade | % Improvement in COP_cascade | % Decrement in EDR_cascade | % Improvement in Exergetic Efficiency_cascade |
|-----------------------------------|----------|-------|----------------------|-------------|-------------|------------------------------|------------------------------|----------------------------|---|
| 30 | 0.7486 | 3.121 | 0.2427 | 0.7885 | 1.997 | 0.3337 | 5.323 | -36.02 | 37.51 |
| 35 | 0.7410 | 3.163 | 0.2402 | 0.7827 | 2.008 | 0.3325 | 5.627 | -36.52 | 38.41 |
| 40 | 0.7353 | 3.195 | 0.2384 | 0.7784 | 2.016 | 0.3315 | 5.856 | -36.90 | 39.09 |
| 45 | 0.7312 | 3.219 | 0.2370 | 0.7752 | 2.022 | 0.3309 | 6.023 | -37.17 | 39.59 |

Thermodynamic first law energy performances of integrated single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems with varying Condenser temperature is shown in table -5 respectively. It was observed that by increasing VARS Condenser temperature, the thermodynamic first law (energy) performance is decreases while second law (exergy)efficiency is decreases and exergy

destruction ratio is increases. Similarly, Thermodynamic performances of cascaded single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems with variation of generator temperature is shown in table-6 respectively. It was observed thermodynamic performances is decreases, by increasing generator temperature.

Table-5 Effect of condenser temperature on thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1233zd(E) ecofriendly refrigerants at MTC evaporator temperature=-65°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Condenser temperature of VARS (°C) | COP_VARS | EDR | Exergetic Efficiency | COP_cascade | EDR_cascade | Exergetic Efficiency_cascade | % Improvement in COP_cascade | % Decrement in EDR_cascade | %Improvement in Exergetic Efficiency_cascade |
|------------------------------------|----------|-------|----------------------|-------------|-------------|------------------------------|------------------------------|----------------------------|--|
| 30 | 0.7472 | 3.129 | 0.2422 | 0.7874 | 2.003 | 0.3330 | 5.38 | -36.11 | 37.61 |
| 32 | 0.7449 | 3.141 | 0.2415 | 0.7857 | 2.004 | 0.3328 | 5.470 | -36.26 | 37.94 |
| 34 | 0.7423 | 3.156 | 0.2406 | 0.7837 | 2.006 | 0.3327 | 5.574 | -36.44 | 38.25 |
| 35 | 0.7410 | 3.163 | 0.2402 | 0.7827 | 2.008 | 0.3325 | 5.627 | -36.52 | 38.41 |
| 36 | 0.7398 | 3.170 | 0.2398 | 0.7818 | 2.070 | 0.3323 | 5.678 | -36.61 | 38.56 |
| 38 | 0.7374 | 3.183 | 0.2390 | 0.780 | 2.013 | 0.3319 | 5.773 | -36.76 | 38.84 |
| 40 | 0.7353 | 3.195 | 0.2384 | 0.7784 | 2.016 | 0.3315 | 5.856 | -36.90 | 39.09 |
| 42 | 0.7336 | 3.205 | 0.2378 | 0.7771 | 2.019 | 0.3313 | 5.925 | -37.01 | 39.30 |
| 44 | 0.7322 | 3.213 | 0.2373 | 0.7760 | 2.021 | 0.3310 | 5.983 | -37.11 | 39.47 |
| 45 | 0.7315 | 3.217 | 0.2371 | 0.7755 | 2.022 | 0.3309 | 6.009 | -37.15 | 39.55 |

Table-6 Effect of generator temperature on thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1233zd(E) ecofriendly refrigerants at MTC evaporator temperature=-65°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | COP_VARS | EDR_VARS | Exergetic Efficiency_VARS | COP_MTC | EDR_MTC | Exergetic Efficiency_MTC | %Improvement in COP_MTC | %Improvement in COP_MTC | %Improvement in COP_MTC |
|------------------------------------|----------|----------|---------------------------|---------|---------|--------------------------|-------------------------|-------------------------|-------------------------|
| 90 | 0.7596 | 2.277 | 0.3052 | 0.8194 | 1.599 | 0.3849 | 7.881 | -29.79 | 26.10 |
| 95 | 0.7532 | 2.510 | 0.2849 | 0.8145 | 1.657 | 0.3761 | 8.132 | -33.98 | 32.10 |
| 100 | 0.7478 | 2.737 | 0.2676 | 0.8103 | 1.715 | 0.3684 | 8.346 | -37.37 | 37.67 |
| 105 | 0.7437 | 2.955 | 0.2528 | 0.8070 | 1.770 | 0.3611 | 8.509 | -40.13 | 42.82 |
| 110 | 0.7410 | 3.163 | 0.2402 | 0.8049 | 1.822 | 0.3544 | 8.618 | -42.40 | 47.53 |
| 115 | 0.7388 | 3.364 | 0.2291 | 0.8031 | 1.873 | 0.3481 | 8.709 | -44.34 | 51.93 |
| 120 | 0.7399 | 3.541 | 0.2202 | 0.8040 | 1.917 | 0.3428 | 8.665 | -45.87 | 55.68 |

Thermodynamic first law energy performances of integrated single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems with varying generator temperature for constant evaporator temperature of -75°C in lower vapour compression cycle is shown in tables -7 for R1233zd(E), R1225ye(Z) and HFO-1336mzz(Z) respectively. It was observed that by increasing VARS Condenser temperature, the thermodynamic first law (energy) performance is decreases while second law (exergy)efficiency is decreases and exergy destruction ratio is increases. Similarly, Thermodynamic performances of cascaded single effect Li/Br-H₂O VARS system cascaded with three stages vapour compression cascaded systems with variation of generator temperature is shown in table-6 respectively. It was observed thermodynamic performances

Table-7(a) Effect of generator temperature on thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1233zd(E) ecofriendly refrigerants at MTC evaporator temperature=-75°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | COP_Cascade | EDR_Cascade | Exergetic Efficiency_Cascade |
|------------------------------------|-------------|-------------|------------------------------|
| 90 | 0.8194 | 1.599 | 0.3849 |
| 95 | 0.8145 | 1.657 | 0.3761 |
| 100 | 0.8103 | 1.715 | 0.3684 |
| 105 | 0.8070 | 1.770 | 0.3611 |
| 110 | 0.8049 | 1.822 | 0.3544 |
| 115 | 0.8031 | 1.873 | 0.3481 |
| 120 | 0.8040 | 1.917 | 0.3428 |

Table-7(b) Effect of generator temperature on improvement in thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1233zd(E) ecofriendly refrigerants at MTC evaporator temperature=-75°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | % improvement in COP_cascade | % decrease in EDR_cascade | % improvement in Exergetic Eff_cascade |
|------------------------------------|------------------------------|---------------------------|--|
| 90 | 7.881 | -29.79 | 26.10 |
| 95 | 8.132 | -33.98 | 32.10 |
| 100 | 8.346 | -37.36 | 37.67 |
| 105 | 8.509 | -40.13 | 42.82 |
| 110 | 8.618 | -42.40 | 47.53 |
| 115 | 8.709 | -44.34 | 51.93 |
| 120 | 8.665 | -45.87 | 55.68 |

Table-7(c) Effect of generator temperature on thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using HFO1336mzz(Z) ecofriendly refrigerants at MTC evaporator temperature=-75°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | COP_cascade | EDR_cascade | Exergetic Efficiency_cascade |
|------------------------------------|-------------|-------------|------------------------------|
| 90 | 0.7950 | 1.790 | 0.3594 |
| 95 | 0.7902 | 1.852 | 0.3507 |
| 100 | 0.7478 | 1.911 | 0.3435 |
| 105 | 0.7437 | 1.968 | 0.3369 |
| 110 | 0.7410 | 2.022 | 0.3309 |
| 115 | 0.7388 | 2.075 | 0.3252 |
| 120 | 0.7399 | 2.122 | 0.3204 |

Table-7(d) Effect of generator temperature on percentage improvement in thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using HFO1336mzz(Z) ecofriendly refrigerants at MTC evaporator temperature=-65°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | % improvement in COP_cascade | % decrease in EDR_cascade | % improvement in Exergetic Efficiency_cascade |
|------------------------------------|------------------------------|---------------------------|---|
| 90 | 4.662 | -21.36 | 17.43 |
| 95 | 4.914 | -26.26 | 23.10 |
| 100 | 5.129 | -30.18 | 28.38 |
| 105 | 5.293 | -33.41 | 33.26 |
| 110 | 5.402 | -36.06 | 37.73 |
| 115 | 5.493 | -38.32 | 41.92 |
| 120 | 5.449 | -40.09 | 45.49 |

Table-7(e) Effect of generator temperature on thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1225ye(Z) ecofriendly refrigerants at MTC evaporator temperature=-65°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | COP_cascade | EDR_cascade | Exergetic Efficiency_cascade |
|------------------------------------|-------------|-------------|------------------------------|
| 90 | 0.7851 | 1.874 | 0.3479 |
| 95 | 0.7532 | 1.936 | 0.3406 |
| 100 | 0.7478 | 1.997 | 0.3337 |
| 105 | 0.7437 | 2.055 | 0.3274 |
| 110 | 0.7410 | 2.11 | 0.3216 |
| 115 | 0.7388 | 2.163 | 0.3161 |
| 120 | 0.7399 | 2.211 | 0.3115 |

Table-7(f) Effect of generator temperature on percentage improvement in thermodynamic performances of Integrated single effect Li/Br-H₂O VARS using R1225ye(Z) ecofriendly refrigerants at MTC evaporator temperature=-75°C, T_Eva_VARS= 5°C, Approach=, 5°C

| Generator temperature of VARS (°C) | % improvement in COP_cascade | % decrease in EDR_cascade | % improvement in Exergetic Efficiency_cascade |
|------------------------------------|------------------------------|---------------------------|---|
| 90 | 3.359 | -17.69 | 17.43 |
| 95 | 3.612 | -22.87 | 23.10 |
| 100 | 3.827 | -27.06 | 28.38 |
| 105 | 3.991 | -30.48 | 33.26 |
| 110 | 4.10 | -33.29 | 37.73 |
| 115 | 4.192 | -35.70 | 41.92 |
| 120 | 4.148 | -37.58 | 45.49 |

3. Conclusions

Following conclusions were drawn from present investigations

- By reducing the exergy destruction rate by using HFO refrigerants therefore, sustainability improved.
- The best thermodynamic performances were observed by using R1234ze(Z) and R1233zd(E), HFO-1336mzz(Z), and R1225ye(Z) and R1234ze(E) and R1243zf performance
- The lowest thermodynamic performances were found by using R1234yf in cascaded system in lower circuit up to a VCR evaporator temperature
- In single cascading with VARS, at low temperature applications up to -30°C evaporator temperature, HFO ecofriendly refrigerants (R-1234ze(Z), R-1234ze(E), R1233zd(E), R-1243zf, R1225ye(Z), HFO-1336mzz(Z) and R1234yf will be certainly useful for replacing HFC, HCFC and CFC refrigerants, while R1224yd(Z) will be suitable for -10°C above evaporator temperature for replacing R134a.
- In single cascading with VARS, at low temperature applications up to -50°C evaporator temperature, HFO ecofriendly refrigerants (R1225ye(Z), R1233zd(E), HFO-1336mzz(Z) and R1234yf will be certainly useful for replacing HFC, HCFC and CFC refrigerants.
- In the double cascading with VARS, at low temperature applications up to -75°C evaporator temperature, HFO ecofriendly refrigerants (R1225ye(Z), R1233zd(E), HFO-1336mzz(Z) will be certainly useful for replacing HFC, HCFC and CFC refrigerants and can be better than replacing R134a
- In the triple cascading with VARS, at ultra-low temperature applications up to -150°C evaporator temperature, HFO ecofriendly refrigerants (R1225ye(Z), HFO-1336mzz(Z) will be certainly useful for replacing R32, and, HCFC and CFC refrigerants.

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