International Journal of Research in Engineering and Innovation
(IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Performance evaluation of triple effect Li/Br-H_2O vapour absorption refrigeration system with three cascaded vapour compression refrigeration systems using HFO refrigerants for ultra-low temperature applications

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Abstract

In this paper, the triple effect Li/Br-H_2O absorption-compression three staged cascade refrigeration systems have been analyzed theoretically using exergy-exergy concepts for ultra-low temperature cooling applications for freeze drying, pharmaceuticals, chemical and petroleum industries. It comprises of a triple effect H_2O-LiBr series & parallel flow vapour absorption refrigeration system in higher temperature cycle cascaded with vapour compression refrigeration cycles using HFO refrigerants (R1234yf , R1224yd(Z),R1234ze(Z), R1243zf, R1225ye(Z), R1233zd(E) , R1234ze(Z) & HFO-1336mzz(z) in medium temperature cycle (to the MTC evaporator temperature of -30ºC and -50ºC)and HFO refrigerants (R1225ye(Z), R1233zd(E) , HFO-1336mzz(z) in intermediate temperature cycle(ITC) (to the ITC evaporator temperature of -75ºC and -95ºC)and HFO refrigerants (R1234yf , R1234ze(Z), R1243zf, R1225ye(Z), R1233zd(E) , R1234ze(Z) & HFO-1336mzz(z) in ultra-low temperature cycle(LTC) (to the ITC evaporator temperature of -135ºC and -150ºC). The three staged cascade absorption-compression systems provide ultra-lower temperature i.e. 123K , 138 K at lesser running cost using waste available from the exhaust of gas turbine power plant or steam turbine power plant to run the triple effect vapour absorption refrigeration system which reduces the overall high grade energy (electricity) consumption of the cascaded compression-absorption refrigeration systems. It was found that triple effect Li/Br-H_2O) cascaded system using R1233zd(E) in medium temperature cycle, R1225ye(Z) and HFO-1336mzz(Z) gives best thermodynamic energy and exergetic performances than other cascaded refrigeration systems in terms of 181.2% of exergetic performance improvement while first law energy performance was 6.25%.

Keywords: Triple effect compression absorption systems, Thermodynamic performance, HFO Refrigerants, Energy-Exergy Analysis

1. Introduction

Khaliq and Kumar [1] carried out thermodynamic analysis of double effect vapour absorption refrigeration system and the computed effects of the generator, absorber, evaporator and condenser temperatures on the system performance and shown that the exergy destructions occurred significantly in the generators, absorber, evaporator and heat exchangers.
Surendra Kumar Agrawal, Rajesh Kumar, Abdul Khaliq [2] also conducted the energy and exergy analyses of a new solar driven integrated of absorption refrigeration cycle using ejector and found improvement in performances. Gomri [3] conducted energy and exergy analysis of triple effect absorption cycles for the production of chilled water and found that the maximum COP of 1.766 of the triple effect cycle at 4°C of evaporator temperature, 33 °C of condenser temperature and 190°C of high pressure generator temperature. Gomri and Hakimi [4] carried out the energy and exergy analysis of double effect vapour absorption system and found that the COP increases by increasing (LPG) temperature. Also concluded that the COP decreases with increasing (HPG) temperature. Md.Azhar & M. Altamush Siddiqui [5] carried out energy and exergy analysis of triple effect absorption refrigeration system shown the effect of COPs for different operating conditions and reference environment conditions on the system performance. Gebreslassie et al. [6] performed the first and second law analysis for half to triple effect water–Li/Br absorption system, and concluded that at higher heat source temperature, the COP and exergetic efficiency decreases

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https://doi.org/10.36037/IJREI.2020.4606

slowly. 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.

Radhey Shyam Mishra [8-10] carried out thermodynamic performance of the HFO refrigerants in the medium temperature compression stage between 5ºC to -50ºC and NH_3H_2O, Li/Br-H_2O 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 (-50ºC to 95ºC) 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 NH_3–H_2O in the high temperature absorption stage and HFO refrigerants at the evaporator temperature of 223K (-50ºC) and R245fa in in the medium temperature compression cycle for evaporator temperature of -95ºC 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 -130ºC . It is found that R1233zd (E), R1225ye(Z) and HFO-1336mzz(z) gives better thermodynamic performances than using R1243yf absorption chillers present opportunities to utilize sustainable fuels in the production of chilled water. By any source of heat energy such as solar, waste heat and gases, the vapour absorption refrigeration system to be capable of be driven since the absorption machines are heat operated systems which can utilized by the several form of energy [8]. Similarly, the energy source can be selected depending on its availability and the cost incurred in procuring and converting it into useful energy. A number of energy sources, along with solar energy and waste heat may prove to be the cheapest provided they are available satisfactorily at the location where the absorption machine is to be installed [9].

The waste heat is usually available from the processor power industries which can be used to operate the absorption machine for air conditioning of places close to the plant because transporting the waste heat to a long distance may bring down its energy level.

Here, large capacity air conditioner can be installed if adequate energy is available in the waste heat at the point of its disposal. Similarly, the absorption system can also be operated by resources of solar energy provided, because it is available in most of the days, when cooling is required and there is plenty open space for the solar collectors to be installed [10].

2. Role of HFO refrigerants for replacing high GWP Refrigerants

Some aspects of global warming in general, and the implications for refrigerants and refrigerator first law (energy) and second law exergetic) efficiency in particular, are very important to be considered for designing of refrigeration systems. The concepts of Global Warming Potential (GWP) and Total Equivalent Warming Impact (TEWI) are also be important for consideration in particularly in HFO refrigerants. However, GWP is an index which allows a simple comparison to be make between the with warming effects of different gases on a kg to kg basis relative to carbon. Therefore, GWP depends both on the lifetime of a substance in the atmosphere and its infrared absorption capacity. The overall warming effect of operating refrigeration system for its entire life is measured by its TEWI. Chloro-flouro-carbons (CFCs) which have been widely used as refrigerants are powerful greenhouse gases with high GWPs. Because of the bank of CFCs in refrigerating systems, their levels in the atmosphere are still increasing and it will be some time before refrigerant changes will be effective in reducing the warming effects of refrigerant releases. Hydrocarbons(HC) are in limited use due to its flammable nature. However, hydroflourocarbons (HFC) are also to be limited due to its higher GWP. Similarly, ammonia (R-717) all have a part to play as substitute refrigerants but due to its toxic nature and not used for domestic applications but can easily be used in industrial refrigeration and air conditioning. Refrigerator energy and exergetic efficiencies are very important in terms exergy of product to exergy of fuel for reducing CO_2 emissions. Therefore, ultra-low GWP ecofriendly HFO refrigerants can solve such problems due to its similar to thermodynamic performances (even more) for replacing CFC, HCFC and HFC refrigerants. The studies carried out so far on the double and triple effect cycles in the use of HFO refrigerants up to evaporator temperature of -50oC in cascaded vapour compression refrigeration systems. to some extent, the effect of HFO refrigerants in the intermediate temperature cycle at -75oC and -95oC 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.

3. Results and Discussion

The following new systems have been considered for thermodynamic evaluations;

System-1

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -150°C.

System-2

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -150ºC.

System-3

Li/Br-H_2O Triple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf in medium temperature cycle at evaporator temperature =-50ºC, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -150ºC.

System-4

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234yf in medium temperature cycle at evaporator temperature =-50ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -150ºC.

Following numerical values have been used for validation of code developed for cascaded triple effect Li/Br-H_2O systems using ecofriendly refrigerants

- Generator temperature= 180ºC
- Absorber temperature=35ºC
- Condenser temperature =35ºC
- VARS evaporator temperature=10ºC
- load on VARS Evaporator= 175 kW
- Ambient (dead state) temperature=25ºC
- Temperature overlapping in MTC = 10ºC
- VCR evaporator temperature of MTC=-50ºC
- VCR evaporator temperature of ITC=-95ºC
- VCR evaporator temperature of LTC=-150ºC
- VCR compressor efficiency of MTC= 80%
- VCR compressor efficiency of ITC= 80%
- VCR compressor efficiency of MTC= 80%
- Ambient (dead state) temperature=25ºC

Thermodynamic first law energy performances of integrated triple effect Li/Br-H_2O VARS system cascaded with three stages vapour compression cascaded systems shown in table 1(a) respectively. It was observed that system-2 has lowest thermodynamic performances than system-1, however first law thermodynamic performance improvement is less. Similarly, Thermodynamic second tlaw exergy performances of cascaded triple effect Li/Br-H_2O VARS system cascaded with three stages vapour compression cascaded systems shown in table-1(b) respectively. It was observed that system-2 has higher thermodynamic exergetic performances than system-1. However, second law thermodynamic exergetic performance improvement for -150ºC 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 exegetic performances of double stage cascaded integrated system-1 is higher than double stage cascaded integrated system-2 at evaporator temperature of -95ºC.It means by putting HFO-1336mzz(Z) in intermediate temperature cycle gives lower first and second law thermodynamic performances than using R-1225ye(Z)

Table-1(a) Thermodynamic first law (energetic) performances of cascaded triple- effect Li/Br-H_2O VARS at evaporator temperature=-150ºC

Integrated system	COP_{VARS}	COP_{MTC}	COP_{ITC}	COP_{LTC}	%Improvement in COP_{MTC}	%Improvement in COP _ITC	%Improvement in COP_{LTC}
System1	1.623	1.728	1.796	1.724	6.472	10.64	6.254
System2	1.623	1.657	1.733	1.67	2.085	6.784	2.922
System3	1.623	1.728	1.787	1.722	6.472	10.13	6.094
System4	1.623	1.657	1.725	1.668	2.085	6.31	2.776

Table-1(b) Thermodynamic second law (exergetic) performances of cascaded triple- effect Li/Br-H2O VARS at evaporator temperature=-150ºC

Integrated system	ETA_{VARS}	ETA_{MTC}	ETA_{ITC}	ETA_ LTC	%Improvement in ETA_{MTC}	%Improvement in ETA_{ITC}	%Improvement in ETA_{LTC}
System1	0.2514	0.4949	0.6116	0.7043	96.86	143.3	180.1
System2	0.2514	0.4580	0.5720	0.6643	82.9	127.5	164.2
System3	0.2514	0.4949	0.6058	0.7068	96.86	141.0	181.2
System4	0.2514	0.4580	0.5667	0.6669	82.9	125.4	165.3

The following new systems have been considered for thermodynamic evaluations;

System-5

Li/Br-H_2O Triple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-6

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-7

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -150ºC.

System-8

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -150ºC.

System-9

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-10

Li/Br-H_2O Tripple-Effect vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1233zd(E) in medium temperature cycle at evaporator temperature =-50ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -95ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135ºC.

Following numerical values have been usedfor validation of code developed for Integrated Li/Br-H_2O VARS using ecofriendly refrigerants

- Generator temperature= 180ºC
- Absorber temperature=35ºC
- Condenser temperature =35ºC
- VARS evaporator temperature=10ºC
- load on VARS Evaporator= 175 kW
- Ambient (dead state) temperature=25ºC
- Temperature overlapping in MTC = 10ºC
- VCR evaporator temperature of MTC=-30ºC
- VCR evaporator temperature of ITC=-75ºC
- VCR evaporator temperature of LTC=-135ºC
- VCR compressor efficiency of MTC= 80%
- VCR compressor efficiency of ITC= 80%
- VCR compressor efficiency of MTC= 80%
- Ambient (dead state) temperature=25ºC

Thermodynamic first law energy performances of integrated triple effect Li/Br-H_2O VARS system cascaded with three stages vapour compression cascaded systems shown in table 2(a) respectively. It was observed that system-6 has highest thermodynamic performances than other integrated systems. However, first law thermodynamic performance improvement is higher of system-5 and lowest for system-7. Similarly, Thermodynamic first law exergy performances of integrated triple effect Li/Br-H_2O VARS system cascaded with three stages vapour compression cascaded systems shown in table-2(b) respectively. It was observed that system-8 has lowest thermodynamic exergetic performances. Similarly, second law thermodynamic exergetic performance improvement is less of system-8 as compared to other systems at -75ºC of evaporator temperature. The exergy destruction ratio in these systems are presented in table-2. It is seen that system 5 has maximum percentage in the exergy decrement.

Table-2(a) Thermodynamic first law (energetic) performances of cascaded tripple- effect Li/Br-H_2O VARS using ecofriendly refrigerants at LTC evaporator temperature=-135ºC, $T_{\_EVA\_VARS}$=10ºC, $T_{\_EVA\_MTC}$=-30ºC, $T_{\_EVA\_ITC}$= -75ºC, $T_{\_EVA\_\_LTC}$ = -135ºC

Integrated system	$COP_{\_VARS}$	$COP_{\_MTC}$	$COP_{\_ITC}$	COP _ LTC	%Improvement in $COP_{\_MTC}$	%Improvement in $COP_{\_ITC}$	%Improvement in $COP_{\_LTC}$
System5	1.623	2.066	2.117	2.024	27.31	30.42	24.74
System6	1.623	2.011	2.079	1.987	23.93	28.12	22.41
System7	1.623	2.011	2.075	1.994	23.93	28.12	22.84
System8	1.623	2.047	2.109	2.015	26.11	29.93	24.39
System9	1.623	2.033	2.098	2.002	25.3	29.29	23.37

Table-2(b) Thermodynamic second law (exergetic) performances of cascaded triple- effect Li/Br-H_2O VARS using ecofriendly refrigerants at LTC evaporator temperature=-135ºC, $T_{\_EVA\_VARS}$=10ºC, $T_{\_EVA\_MTC}$=-30ºC, $T_{\_EVA\_ITC}$= -75ºC, $T_{\_EVA\_\_LTC}$ = -135ºC

Integrated system	ETA_{VARS}	ETA_{MTC}	ETA_{ITC}	ETA_{LTC}	%Improvement in ETA_{MTC}	%Improvement in ETA_{ITC}	%Improvement in ETA_{LTC}
System5	0.2514	0.5039	0.5721	0.6714	100.4	127.6	167.1
System6	0.2514	0.4794	0.5542	0.6457	90.69	120.5	156.8
System7	0.2514	0.4794	0.5542	0.6522	90.69	120.5	159.4
System8	0.2514	0.4951	0.5686	0.6666	96.93	126.2	165.2
System9	0.2514	0.4892	0.5832	0.6547	94.58	124.0	160.4

Table-2(C) exergy Destruction Ratio and % decrement cascaded triple- effect Li/Br-H_2O VARS using ecofriendly refrigerants at LTC evaporator temperature=-135ºC, $T_{\_EVA\_VARS}$=10ºC, $T_{\_EVA\_MTC}$=-30ºC, $T_{\_EVA\_ITC}$= -75ºC, $T_{\_EVA\_\_LTC}$ = -135ºC

Integrate system	EDR_{VARS}	EDR_{MTC}	EDR_{ITC}	EDR_{LTC}	% decrement in EDR_{MTC}	%decrement in EDR_{ITC}	%decrement in EDR_{LTC}
System-5	2.978	0.9848	0.748	0.4894	-66.93	-74.88	-83.56
System-6	2.978	1.086	0.8043	0.5496	-63.53	-72.99	-81.57
System-7	2.978	1.086	0.8043	0.5333	-63.53	-72.99	-82.09
System-8	2.978	1.020	0.7581	0.50	-65.75	-74.52	-83.2
System-9	2.978	1.044	0.7755	0.5275	-64.93	-73.96	-82.28

4. Conclusions

A theoretical analysis has been presented to predict the performance of cascaded triple effect Li/Br-H_2O using energy and exergy principles. A triple effect H_2O-LiBr VARS is coupled to the VCRS using HFO refrigerant through the cascade heat exchanger by the three times time. These systems have its utilities in ultralow evaporator temperatures ranging from ice manufacturing to frozen food and ultra-low temperature applications. Following conclusions were drawn from present investigation

- In single cascading with VARS, at low temperature applications up to -30ºC 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 -10ºC above evaporator temperature for replacing R134a.
- In single cascading with VARS, at low temperature applications up to -50ºC 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 -75ºC 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 R32, R245fa and R134a.
- In the triple cascading with VARS, at ultra-low temperature applications up to -135ºC evaporator temperature, HFO ecofriendly refrigerants (R1225ye(Z), HFO-1336mzz(Z) will be certainly useful for replacingR32, and, HCFC and CFC refrigerants.

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Cite this article as: R.S. Mishra, Performance evaluation of triple effect Li/Br-H2O vapour absorption refrigeration system with three cascaded vapour compression refrigeration systems using HFO refrigerants for ultra-low temperature applications, International Journal of Research in Engineering and Innovation Vol-4, Issue-6 (2020), 338-342. https://doi.org/10.36037/IJREI.2020.4606