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Performance evaluation of NH_3H_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

The potential alternative refrigeration technology due to the utilization of energy resources is the vapour compression–absorption refrigeration system. The main issues observed with NH3-H2O vapour absorption refrigeration system are low overall COP and large size of system which is mainly due to the reduced thermodynamic performance of absorption systems. It was also found that at low generator temperatures, the ejector-assisted absorption portion provides better thermodynamic performance than the conventional absorption system adapted in vapour compression–absorption hybrid refrigeration system. The overall performance of system can be improved by increasing the evaporator and generator temperature and by decreasing the absorber, cascade condenser and condenser temperature. Simulation results show that the overall COP of integrated cascaded system is improved by 56 % to 94 %. whereas the improvement of exergetic efficiency is ranging from 25.2% is observed in the absorption section. The total irreversibility of the system is reduced by 7.55% to 28.25%.

Keywords: HFO refrigerants, Thermodynamic performance evaluation, NH_3-H_2O vapour absorption refrigeration, HFO refrigerants

1. Introduction

The potential alternative refrigeration technology due to the utilization of energy resources is the vapour compression–absorption refrigeration system. The main issues observed with VARS is low overall COP and large size of system which is mainly due to the reduced thermodynamic performance of absorption systems. It was also found that at low generator temperatures, the ejector-assisted absorption portion provides better thermodynamic performance than the conventional absorption system adapted in vapour compression–absorption hybrid refrigeration system. The overall performance of system can be improved by increasing the evaporator and generator temperature and by decreasing the absorber, cascade condenser and condenser temperature. In the present study, the performance of vapour compression–absorption cascaded refrigeration system (VCACRS) is studied and the results are compared with the exergy evaluation. The quantitative difference in two approaches is presented which necessitates the need to employ modified approach. The expressions are formulated for effective temperature and real irreversible loss for different components of VCACRS.

2. Integrated Vapour compression absorption refrigeration systems

Canan et.al. [1] carried out studied on LiBr–H2O absorption refrigeration section in compression–absorption cascade refrigeration cycle using with using different (R134a, R-410A) refrigerants in the compression refrigeration cycle and and found electrical energy consumption in the cascade refrigeration cycle is 48–51% lower than classical vapour compression refrigeration cycles that use R134a and R-410A as working fluids under the same operating conditions at evaporator temperature of 263 K and a condenser temperature of 313 K while using R134a, in VCRS the thermal energy consumption of cascade refrigeration cycle could be reduced by 35% and also overall coefficient of performance ($COP_{cyclegen}$) could be improved by 33%.

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Gulshan sachdeva et.al [2] studied , vapor compression–absorption cascade system using Ammonia–water is considered as the working fluid in absorption cycle and R407C as the working fluid in vapour compression cycle section and carried out second law analysis has been done for the pair in absorption section and determined the exergy destruction (irreversibility rate) in each components of cascade system, for a wide range of cooling capacity by considering a variable speed reciprocating compressor and found the significant reduction in electrical energy consumption. Also found strong effect of effect of varying the generator temperature, effectiveness of solution heat exchanger, inlet temperature of external fluids in evaporator/condenser and some other variables on the system using Coefficient of structural bond (CSB) analysis to quantify the effect of solution heat exchanger and concluded a great scope of improvement to reduce the irreversibility rate of the whole system.

Vaibhav Jain et.al [3] developed, a thermodynamic model for cascaded vapor compression-absorption system consists of a vapor compression refrigeration system (VCRS) coupled with single effect vapor absorption refrigeration system and carried out comparative performance analysis of cascaded system along with independent VCRS for a design capacity of 66.67 kW using first and second laws, and found that the electric power consumption in cascaded system is reduced by 61%. Also computed rational efficiency and effect of operating parameters (i.e., superheating, subcooling, cooling capacity, inlet temperature, product of effectiveness and heat capacitance of external fluids0 on the COP, total irreversibility and rational efficiency of the cascaded system using environment friendly refrigerants such as R410A, R407C and R134. Dario Colorado-Garrido and V. M. Velazquez [4] studied a compression–absorption cascade system LiBr/H_2O using absorption refrigeration cycle with different working fluids(i.e. ammonia, R134a and carbon dioxide) in vapour compression refrigeration cycle and evaluated performance using first and second laws of thermodynamic analysis and simulated the results for finding the best working fluid performance s(i.e. coefficient of performance, exergetic efficiency, irreversibility of the main components of the system, total irreversibility of the system). Also found the highest irreversibilities occurred in the cascade heat exchanger using carbon dioxide or ammonia, and observed that this value decreased by using R134a. The highest value of coefficient of performance is observed by using R134a–LiBr/ H_2O system with the minimum of irreversibility in the absorber and generator within a range of generator temperature from 339 to 345 K. M. Dixit [5] analyzed. absorption-compression cascade refrigeration, comprising of a VCR system using CO2, NH3 and R134a in low temperature stage and a VAR system at the high temperature stage using H_2O-LiBr refrigerant and developed a mathematical model using energy and exergy analysis and found the major source of exergy destruction are cascade condenser, compressor and refrigerant throttle valve

Radhey Shyam Mishra [6] carried out thermodynamic performance of the HFO refrigerants in the medium temperature compression stage between 5ºC to -50ºC and NH_3H_2O refrigerants in the absorption stage and its overall effect on the cascade system is presented. 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. The above investigator has not studied the effect of ecofriendly HFO refrigerants (R1233zd(E), R1225ye(Z) and HFO-1336mzz(z)) in the altra low temperature range from -50ºC to -130ºC respectively. This paper mainly deals the effect of HFO ecofriendly refrigerants in the above range for cryogenic applications.

3. Results and Discussion

The following new systems have been considered for thermodynamic performance evaluations;

System-1

NH_3H_2O 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-2

NH_3H_2O 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

NH_3H_2O 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 =-30ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -75ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-4

NH_3H_2O vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1234ze(E) in medium temperature cycle at evaporator temperature =-30ºC, R1233zd(E) in intermediate temperature cycle at evaporator temperature = -75ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-5

NH_3H_2O vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1243zf in medium temperature cycle at evaporator temperature =-30ºC, R1233zd(E) in intermediate temperature cycle at evaporator temperature = -75ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-6

NH_3H_2O vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1243zf in medium temperature cycle at evaporator temperature =-30ºC, R1233zd(E) in intermediate temperature cycle at evaporator temperature = -75ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-7

NH_3H_2O vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1243zf in medium temperature cycle at evaporator temperature =-30ºC, R-1225ye(Z) in intermediate temperature cycle at evaporator temperature = -75ºC and using HFO-1336mzz(Z) in lower temperature cycle at evaporator temperature = -135ºC.

System-8:

NH_3H_2O vapour absorption refrigeration system at -1ºC of evaporator temperature cascaded with three stages vapour compression refrigeration system using R1243zf in medium temperature cycle at evaporator temperature =-30ºC, HFO-1336mzz(Z) in intermediate temperature cycle at evaporator temperature = -75ºC and using R-1225ye(Z) in lower temperature cycle at evaporator temperature = -135ºC.
Following numerical values have been used for validation of code developed for Integrated NH_3-H_2O VARS using ecofriendly refrigerants.

- Generator temperature= 130ºC
- Absorber temperature=35ºC
- Condenser temperature =35ºC
- VARS evaporator temperature=-1ºC
- load on VARS Evaporator= 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%
- Refrigeration Load=35.kW.

Thermodynamic first law energy performances of integrated NH_3-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 law exergy performances of integrated NH_3-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 -100ºC.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: Thermodynamic first (Energy) law performance of three stages cascade vapour compression refrigeration system cascade with NH_3-H_2O VARS ($T_{\_EVA\_LTC}$ =-150°C, $T_{\_EVA\_ITC}$=-95°C, $T_{\_EVA\_MTC}$=-50°C)

Integrate system	First law (energetic) Efficiency $COP_{\_VARS}$	First law (energetic) Efficiency $COP_{\_MTC}$	First law (energetic) Efficiency $COP_{\_ITC}$	First law (energetic) Efficiency $COP_{\_LTC}$	% Improvement in $COP_{\_MTC}$	%Improve-ment in $COP_{\_ITC}$	%Improve-ment in $COP_{\_LTC}$
System-1	0.322	0.5022	0.6028	0.6251	55.96	87.21	94.13
System-2	0.322	0.5022	0.6011	0.6259	55.98	86.69	94.39

Table- 1(b): Thermodynamic exergy performance of three stages cascade vapour compression refrigeration system cascade with NH_3-H_2O VARS ($T_{\_EVA\_LTC}$ =-150°C, $T_{\_EVA\_ITC}$=-95°C, $T_{\_EVA\_MTC}$=-50°C)

Integrated system	Second law (exergetic) Efficiency $ETA_{\_VARS}$	Second law (exergetic) Efficiency $ETA_{\_MTC}$	Second law (exergetic) Efficiency $ETA_{\_ITC}$	Second law (exergetic) Efficiency $ETA_{\_LTC}$	%Improvement in $ETA_{\_MTC}$	%Improvement in $ETA_{\_ITC}$	%Improvement in $ETA_{\_LTC}$
System-1	0.2475	0.3056	0.3211	0.2662	23.5	29.74	7.552
System-2	0.2475	0.3056	0.3174	0.2720	23.5	28.25	9.901

Thermodynamic first law energy performances of integrated NH_3-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 NH_3-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 -75°C of evaporator temperature.

Table- 2(a): Thermodynamic first law (Energy) performance of three stages cascade vapour compression refrigeration system cascade with NH_3-H_2O VARS for ultra-low temperature applications ($T_{\_EVA\_LTC}$ =-135°C, $T_{\_EVA\_ITC}$=-75°C, $T_{\_EVA\_MTC}$=-30°C)

Integrated System	First law (energetic) Efficiency $COP_{\_VARS}$	First law (energetic) Efficiency $COP_{\_MTC}$	First law (energetic) Efficiency $COP_{\_ITC}$	First law (energetic) Efficiency $COP_{\_LTC}$	%Improve-ment in $COP_{\_MTC}$	%Improve-ment in $COP_{\_ITC}$	%Improve-ment in $COP_{\_LTC}$
System-3	0.322	0.5485	0.6712	0.7087	70.36	108.4	120.10
System-4	0.322	0.5485	0.6712	0.7115	70.36	108.4	121.0
System-5	0.322	0.5486	0.6712	0.7088	70.37	108.5	120.1
System-6	0.322	0.5486	0.6712	0.7116	70.37	108.5	121.0
System-7	0.322	0.5486	0.6709	0.7085	70.37	108.4	120.0
System-8	0.322	0.5486	0.6698	0.7109	70.37	108.0	120.5

Table- 2(b): Thermodynamic first law (exergy) performance of three stages cascade vapour compression refrigeration system cascade with NH_3-H_2O VARS for ultra-low temperature applications ($T_{\_EVA\_LTC}$ =-130°C, $T_{\_EVA\_ITC}$=-75°C, $T_{\_EVA\_MTC}$) =-30°C

Integrated cascaded three stages VCRS System	Second law (exergetic) Efficiency $ETA_{\_VARS}$	Second law (exergetic) Efficiency $ETA_{\_MTC}$	Second law (exergetic) Efficiency $ETA_{\_ITC}$	Second law (exergetic) Efficiency $ETA_{\_LTC}$	%Improvement in $ETA_{\_MTC}$	%Improvement in $ETA_{\_ITC}$	%Improvement in $ETA_{\_LTC}$
System-3	0.2475	0.2705	0.3117	0.2893	9.326	25.96	16.9
System-4	0.2475	0.2705	0.3117	0.2966	9.326	25.96	19.87
System-5	0.2475	0.2706	0.3118	0.2893	9.356	25.98	16.92
System-6	0.2475	0.2706	0.3118	0.2967	9.356	25.98	19.89
System-7	0.2475	0.2706	0.3112	0.2889	9.356	25.75	16.75
System-8	0.2475	0.2706	0.3092	0.2947	9.356	24.93	19.1

4. Conclusions

Following conclusions were drawn from present investigation

- 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 -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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