Review of Modified Vapor Absorption Refrigeration Cycles

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Abstract:

This paper presents a thorough investigation of various vapor absorption refrigeration cycles, including both simple and complex designs, with the goal of achieving a comprehensive understanding of their performance characteristics. The study evaluates the current state of the art in vapor absorption refrigeration and highlights any recent advancements in this field. A theoretical analysis of different vapor absorption cycles with modifications such as an ejector, generator absorber heat exchanger, and booster compressor has been conducted. These modifications aim to reduce throttling losses and require different mechanical hardware of varying levels of complexity and cost. The optimization of operating temperatures in the cycles is crucial for achieving maximum coefficient of performance (COP) and minimum gas requirements in the evaporator, absorber, and main condenser. Hybrid vapor compression absorption refrigeration systems have significantly higher COP compared to conventional vapor compression refrigeration, triple effect, and GAX systems. The triple effect cycle demonstrates a maximum COP of 1.955, which is 132% higher than the single effect cycle, with a gas requirement reduction of approximately 122% under the same conditions. Compared to the GAX cycle, the HGAX cycle shows better performance in terms of the first and second laws of thermodynamics, although it incurs a higher unit product cost. The ejector cycle has a COP that is 30% higher than the conventional single-effect absorption refrigeration cycle and a cooling capacity for waste heat with large temperature glide that is about 20% higher. In general, alternative cycles offer many benefits to vapor absorption refrigeration systems, such as reduced losses, increased performance, and decreased energy consumption.

Keywords

Hybrid, Compression, Temperature glide, Heat exchanger, Ejector, Configuration

Nomenclature	
COP	coefficient of performance
GAX	generator- absorber- heat exchanger
Tv	throttle valve
SHX	suction heat exchanger
AB	absorber
pr	Pressure ratio
P	pressure
$T_{g,i}$	Temperature at generator inlet
G	generator
T	temperature (K)
PH	preheater
C	condensor
A	absorber
EV	expansion valve
LPLTA	low pressure low temperature absorber
LPHTA	low pressure high temperature absorber
HPA	high pressure absorber

LPE	low pressure evaporator
HPE	high pressure evaporator
$\dot{m}$	mass flow rate
ω	cooling capacity per unit mass of exhaust gas
Subscripts	
i	inlet
o	outlet

Introduction

The world is currently facing two major challenges: an energy crisis and global warming. The energy crisis is caused by the continued use of fossil fuels and the increasing demand for energy. It is estimated that global energy demand will increase by around 71% from 2003 to 2030. Global warming is largely caused by the emission of greenhouse gases from various sources, including conventional vapor compression refrigeration (VCR) systems, which also use electricity that further exacerbates the pressure on primary energy sources. In addition, the strict regulations on chlorofluorocarbon refrigerants have driven research towards more environmentally friendly alternatives, such as water. Effective methods for reducing CO2 emissions include reducing fossil fuel consumption, improving the efficiency of heat pumps and refrigerators, and using low-grade energy.

Absorption systems can be operated using renewable energy sources such as solar, geothermal, biomass energy, and waste heat from industrial and locomotive processes, which have no global warming effect. Moreover, absorption systems have the potential to be improved among the various heat-powered cycles. While the absorption cycle has lower efficiency compared to the vapor compression cycle, the priority is to develop refrigerators and heat pumps that do not harm the environment. Researchers are currently exploring better ways to improve the thermodynamic performance of absorption systems, with the focus on finding suitable configurations or hybrid cycles, utilizing novel refrigerants, and enhancing heat and mass transfers.

There are several reasons for modifying vapor absorption refrigeration cycles, including improving the coefficient of performance (COP), increasing the capacity for a given system and component size, adapting the heat rejection temperature profile to specific requirements, and keeping the temperature of the generator within limits. The GAX absorption refrigeration cycle and multipleeffect absorption refrigeration cycles such as the double-effect and triple-effect absorption refrigeration cycles have been proposed to improve the performance of the absorption refrigeration cycle. Integration of a hybrid compressor or an ejector is also considered an attractive method to enhance the performance of absorption refrigeration cycles. The absorption refrigeration cycle that can utilize waste heat and solar thermal energy as a driving force has garnered increasing attention in recent years

Ejector-absorption combined refrigeration cycle

The vapor absorption refrigeration cycle using an ejector is a novel approach to improve the COP of the system. The system uses the H2O/LiBr pair as a working fluid. The water vapor leaving the generator is divided into two streams. One stream is directed to the low pressure generator where it is condensed to saturated liquid, while the other stream is injected into the ejector. The pressure of liquid water is reduced by a throttle valve to the condensing pressure, and the remaining vapor in the low-pressure generator is also directed to the ejector. The mixture of vapor leaving the ejector is condensed in the condenser, and the liquid exiting the condenser is depressurized to the evaporating pressure by a throttle valve and then further vaporized in the evaporator. The cycle between the high-pressure generator and the absorber is identical to the standard vapor absorption cycle.

Researchers have investigated ejector-absorption refrigeration cycles to improve system performance. Simulation results of the proposed cycle by Hong et al. showed that the COP was 30% higher than that of the conventional single-effect absorption refrigeration cycle under certain working conditions. An exergy analysis by Alexis showed that the ejector had the maximum exergy loss of approximately 38%. Shi et al. proposed a half-effect ejector-absorption cycle to elevate the half-effect cycle. Kumar et al. combined a double-stage ejector cycle with a single-effect absorption cycle. Pourjahan et al. conducted a thermodynamic and cost-effective analysis for a double-effect absorption-ejector refrigeration cycle and predicted an overall reduction of 16% in the annual cost after optimizing the cycle. Farshi et al. performed a thermodynamic analysis on a single-stage effect cycle and compared it with a modified cycle using an ejector to recover pressure from the absorber and increase mixing of the weak solution and refrigerant vapor. Vereda et al. projected several ejector-absorption cycles with an adiabatic absorber to improve performance.

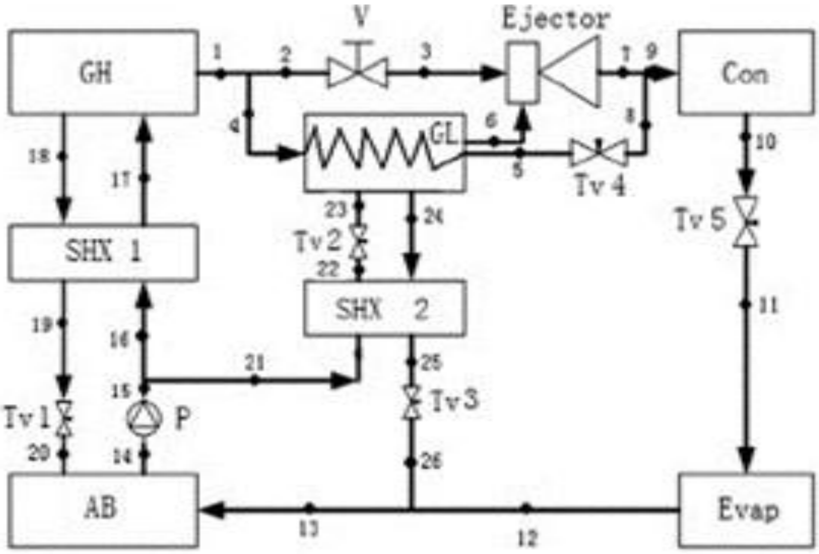

Fig.1. Schematic diagram of a new ejector-absorption combined refrigeration cycle [1]

Hybrid absorption with an integrated low pressure compressor booster

The vapor absorption refrigeration cycle's efficiency can be enhanced by utilizing an integrated low pressure compressor booster. The proposed cycle arrangement, as depicted in Fig. 2, involves the high concentration refrigerant solution departing from the absorber (5) and being pumped (6) via the solution heat exchanger to the generator, where it absorbs heat from the weak solution returning from the generator. Ammonia is separated from the strong solution in the generator (7), with the ammonia vapor exiting the generator (1), while the weak solution returns to the absorber via the solution heat exchanger (8-9) and is depressurized using the solution expansion valve. The ammonia vapor is condensed in the condenser (1-2) at a relatively high pressure (P1) and then depressurized using a refrigerant expansion valve (2-3). Liquid ammonia then vaporizes in the evaporator, producing cooling. The ammonia vapor is pressurized in the compressor and passed to the absorber (4-4c). This modified cycle has three levels of pressure, with the high-density compressed vapor (4c) increasing the absorption rate.

In this cycle, the compressor is situated between the evaporator and the absorber. Ventas et al. [8] developed a numerical model of this cycle with ammonia-lithium nitrate solution as the working pair, achieving a COPmax of 0.645 at Tg,i = 65°C and pr of 2.0, while the single-effect absorption cycle reaches the maximum at Tg, i= 95°C, with COPmax of 0.646. Banker et al. [9] investigated an adsorption cycle that integrated a booster compressor, demonstrating that around 40% energy could be saved with better performance when the temperature difference between the evaporator and condenser exceeded 40°C. Morawetz et al. [10] studied the layout and modifications of the resorption-compression cycle in detail, with the compressor operating in parallel with the basic single-effect absorption cycle in this configuration. The compressor augments the absorption pressure and temperature, decreasing the load on the absorber at a constant evaporation temperature, while also decreasing the evaporation temperature at a constant absorption temperature. If both the temperatures, along with the generation temperatures, are maintained constant, the compressor boosts the cooling power. Boer et al. [11] explained the fundamentals of this layout in more detail. Herold et al. [12] examined the performance of several hybrid vapor compression-absorption cycles based on LiBrH2O, revealing the potential of hybrid cycles in improving the COP of the system. However, a highperformance steam compressor must be developed for the implementation of these hybrid cycles in the near future.

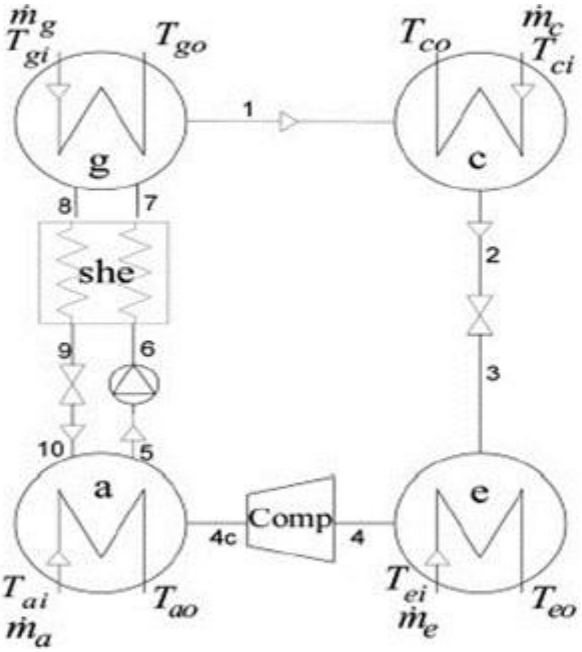

Fig.2. Layout of the absorption cycle integrated with a booster compressor between evaporator and absorber. [8]

Generator- absorber- heat exchanger absorp- tion refrigeration system

The passage describes the use of a Generator-Absorber-Heat Exchanger (GAX) in an ammonia-water absorption refrigeration cycle to reduce expansion losses and potentially improve the Coefficient of Performance (COP). The saturated strong solution from the absorber is pumped and passed on to the

GAX desorber where it boils and generates vapor with higher refrigerant concentration. The weak solution flows back to the absorber via the expansion valve and the GAX absorber. The liberated heat raises the temperature of the solution passing through the GAXD. The ammonia vapor from the generator first enters the GAX desorber and then into the condenser through the rectifier where water vapor is condensed and returns to the generator. The ammonia vapor is converted to liquid ammonia in the condenser and then further cooled in the pre-cooler. The pressure of liquid ammonia is reduced in the expansion valve and it vaporizes in the evaporator by absorbing heat from the cooled products. The weak solution flowing into the absorber from GAXA absorbs ammonia vapor coming from the evaporator to complete the cycle.

Mahmoudi et al. [13] optimized the ammonia-water standard GAX (SGAX) and hybrid GAX (HGAX) absorption refrigeration cycles using parametric studies and genetic algorithm (GA) to maximize COP and exergy efficiency while minimizing cost of unit product. The HGAX cycle demonstrated better performance than the GAX cycle with a COPmax of 0.98 at Tg,i =155 oC. Other studies include a waste heat driven GAX cycle, a thermal oil operated GAX prototype cooling system, a Solar-GAX cycle, and a GAX heat pump for both heating and cooling modes. An ammonia GAX absorption cycle for simultaneous heating and cooling was also designed and developed by Park et al. [18] with novel multi-mode GAX cycles operating in three different modes of cooling and hot water supply with a single hardware.

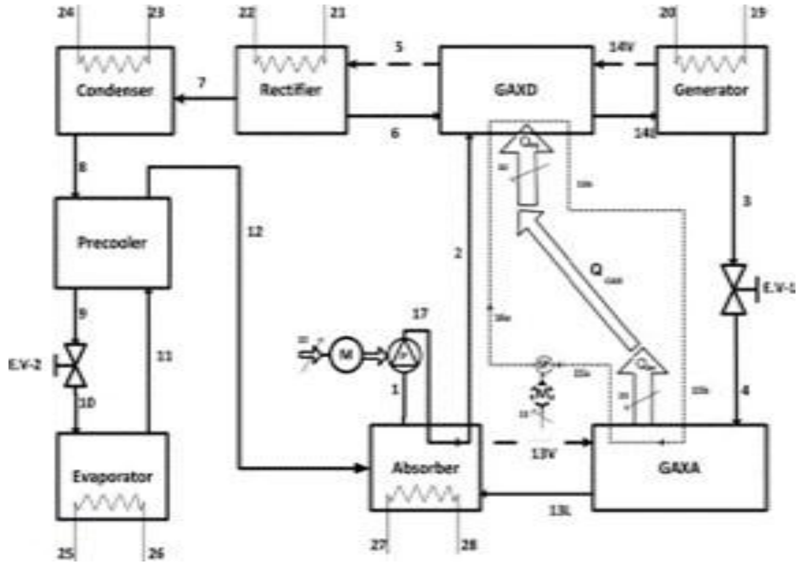

Fig.3. Schematic diagrams of the standard GAX absorption refrigeration cycles. [13]

Hybrid Generator absorber heat exchanger absorption refrigeration system

The HGAX absorption refrigeration cycle is a modification of the GAX cycle where a compressor is added between the condenser precooler and absorber. This allows the ammonia vapor from the evaporator to be compressed to a higher pressure and temperature before entering the absorber, which results in increased heat recovery. However, a limitation of the HGAX cycle is that it requires a cooling medium other than ambient air due to the lower temperature in the absorber.

Dixit et al. [19] conducted an extensive analysis of aqua-ammonia generator-absorber-heat exchanger (GAX) and HGAX absorption refrigeration cycles based on energy and exergy. They calculated the COP and exergetic efficiencies at various operating conditions to study the effect of generator temperature, condenser temperature, and evaporator temperature on them. The maximum COP for the GAX cycle varies between 0.7 and 1.1, while for the HGAX cycle, it lies between 1 and 1.88. Kang et al. [20] proposed four different modifications for the HGAX cycle suitable for different applications. The COP value was found to be almost 24% higher compared to the standard GAX cycle. Ramesh Kumar and Udayakumar [21] simulated a hybrid GAX cycle for air conditioning purposes and found a degassing range of 0.4 corresponding to maximum COP. Yari et al. [22] investigated the HGAX absorption refrigeration system from the perspective of the second law of thermodynamics. They studied the effect of generator temperature on the COP and second law efficiency of GAX and HGAX cycles and established an optimum value for the generator temperature to maximize performance.

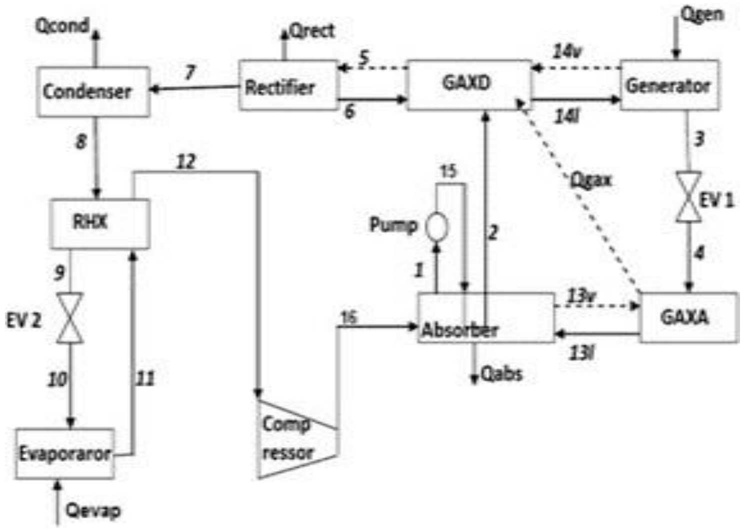

Fig.4.Schematic diagram of hybrid GAX absorption refrigeration cycle [19]

Triple Effect Absorption Refrigeration System

The efficiency of a vapor absorption refrigeration cycle can be significantly increased by employing a triple absorption refrigeration system. The triple effect vapor absorption system consists of three generators and three condensers, as depicted in Figure 5. The weak solution is heated and pressurized before entering the main generator. The strong solution is heated in the main generator to extract the ammonia vapors. The heat released during the condensation of ammonia vapor in the condenser is utilized by the generator G3. The strong solution from the generator passes to the generator G3 via preheater, and more refrigerant vaporizes in the generator G3 and goes to the condenser. The weak solution absorbs heat from the strong solution, and the strong solution then passes to generator G2. More vapor is boiled off in the generator G2 to enter the main condenser. The total refrigerant entering the main condenser in the triple effect cycle will be the sum of the refrigerants from all the generators. The liquefied refrigerant passes to the evaporator via a throttle valve and is vaporized after absorption of heat from the cooled space. The ammonia vapors are absorbed by the strongest solution in the absorber.

Azhar et al. [23] conducted a thermodynamic analysis of LiBr-H2O single, double, and triple effect vapor absorption cycles using LPG and CNG as sources of energy. The operating temperatures in single to triple effect cycles have been optimized for maximum COP and minimum gas requirement using an iterative technique. The maximum COP of the triple effect cycle goes up to 1.955, which is around 132% higher than that of the single effect cycle, with its gas requirement reduced to around 122% at the same conditions. Gomri [24] analyzed the first and second law for triple effect absorption cycles yielding refrigerated water. They found that the highest COP of the triple effect cycle was obtained at certain temperature values. Ratlamwala et al. [25] determined the COP and exergetic efficiency of the triple effect ammonia-water absorption refrigeration system. They demonstrated the effect of different operating variables on the COP of the triple effect system. Gebreslassie et al. [26] evaluated the COP and exergy efficiency for various arrangements of water-LiBr absorption systems. Khaliq et al. [27] performed energy and exergy analyses for a novel solar-driven triple staged refrigeration cycle. The cycle is a combination of ejector refrigeration cycle, absorption refrigeration cycle, and Joule-Thomson cryogenic cycles.

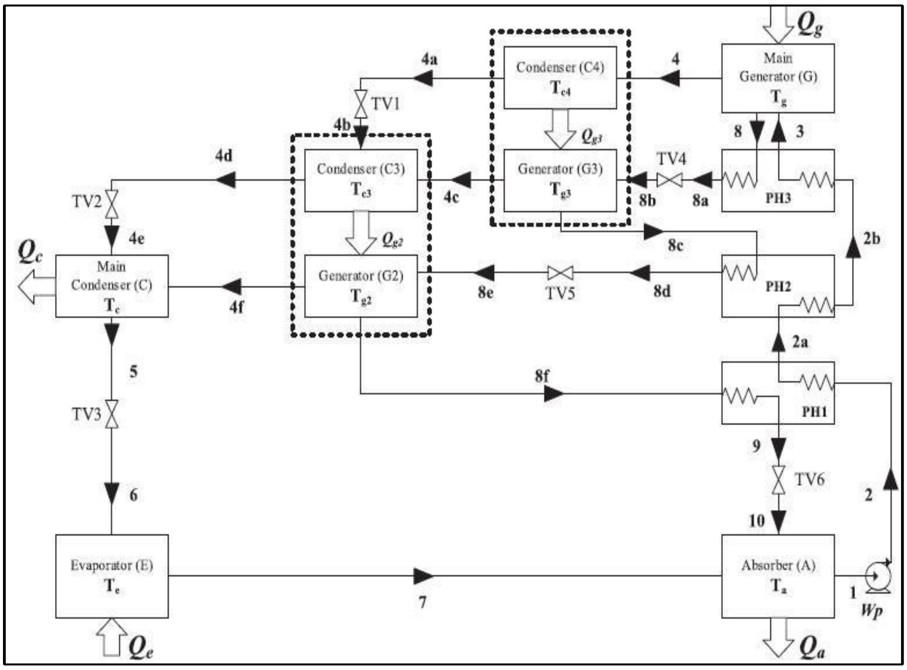

Fig.5.Schematic diagram Triple Effect Absorption Refrigeration System [23]

Novel absorption refrigeration cycle used for waste heat with large temperature glide

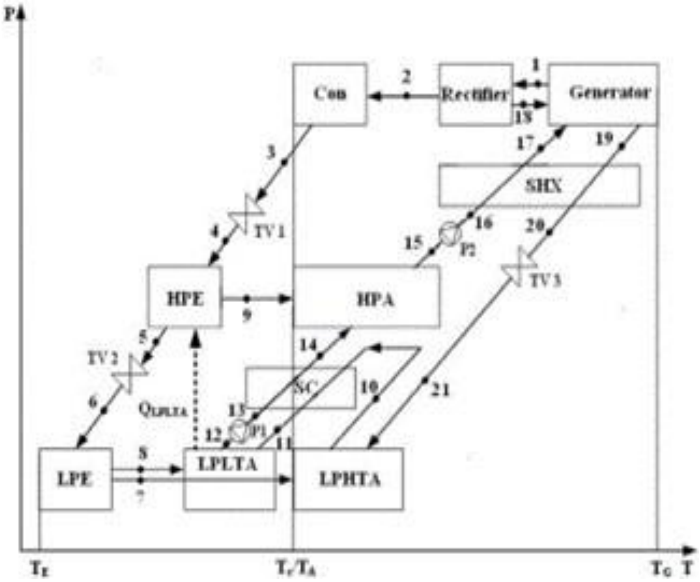

Fig.6.Schematic diagram of absorption refrigeration cycle used for waste heat with large temperature. glide [28]

Utilizing waste heat with large temperature glide can improve the performance of vapor absorption refrigeration cycle by a few percentages. In this proposed cycle, an ammonia-water mixture serves as an absorbent while ammonia acts as the working fluid. The cycle works as follows: the vapor flows into rectifier after leaving the generator, and in the condenser, ammonia vapor is converted to liquid ammonia by rejecting heat to the atmosphere. The low temperature absorber in high-pressure evaporator is cooled by the vaporizing liquid ammonia coming from the throttle valve. The ammonia vapors leaving the high-pressure evaporator proceed towards high-pressure absorber and are subsequently absorbed by the solution absorbent. The unsaturated ammonia vapor out from throttle valve enters the low pressure evaporator and fully evaporates. One stream of the saturated vapor flows into the high temperature absorber and is absorbed by the ammonia-water solution approaching from the generator, while the other stream is absorbed by the absorbent solution coming from high temperature absorber in low temperature absorber. The solution from low temperature absorber is pumped to high-pressure absorber by pump via sub cooler. The solution absorbs ammonia vapor from low-pressure evaporator in high and low temperature absorbers, moves to the high-pressure absorber and further absorbs ammonia vapors. The highly concentrated ammonia mixture in the solution provides more cooling effect to the exhaust gas/water in comparison to the conventional single-effect cycle. Theoretical simulation results show that the cooling capacity per unit mass of exhaust gas of the proposed cycle is about 20% higher than that of a single-effect absorption cycle, especially for the situation that temperature of supplied waste heat is lower and/or refrigeration temperature is lower. Other proposed cycles include the double-lift absorption refrigeration system, the combination of a single-effect absorption refrigeration cycle with a two-stage absorption refrigeration cycle, and the integration of a single-effect cycle and a double-effect cycle with a common evaporator and absorber, which all utilize waste heat recovered from exhaust and cooling water to improve the performance of the combined cycle. A simulation model for analyzing the performance of a CO2/propylene based transcritical cascade refrigeration-heat pump system was also proposed, which predicted an increase of about 6% in the COP of the system for the given range of operating variables by utilizing a vortex tube instead of an expansion valve for recovery of expansion work.

Conclusion

This study extensively evaluates various modifications to vapor absorption refrigeration cycles, including the use of an ejector, generator absorber heat exchanger, booster compressor, and multistage systems. Based on the results of this study, several conclusions can be drawn.

Firstly, for absorption temperatures and condensing temperatures of 40°C and an evaporation temperature of 5°C, an ejector cycle yields a 30% higher COP than the conventional single-effect cycle when the heat source temperature exceeds 122.5°C.

Secondly, the booster compressor cycle enables a reduction in the hot water inlet temperature (Tg,i) by 24°C, provided that pressure ratios (pr) are not higher than 2.0. The COP and cooling capacity remain unchanged.

Thirdly, the GAX and hybrid GAX cycles achieve their maximum COP values (0.9-1.3 and 1.3-1.88, respectively) at generator temperatures ranging from 160°C to 175°C. As the approach temperature increases from 0°C to 14°C, the COP of the GAX cycle decreases by up to 30%, and that of the HGAX cycle decreases by up to 45%.

Fourthly, the triple effect cycle has the highest COP (132%) and requires a low volume flow rate of gases, making it more efficient and economical. The salt concentration in the main generator is lower in the double and triple effect cycles, resulting in a lower generator temperature value.

Lastly, the absorption refrigeration cycle used for waste heat with a large temperature glide always has a lower COP than the conventional single-effect cycle. This is because the ammonia concentration of the solution in the generator of the new cycle is much higher than that of the conventional single-effect cycle, allowing the projected cycle to fully use low-grade heat in the exhaust gas. This increases the ω of the novel cycle up to 20% compared to the conventional singleeffect cycle.

Therefore, the triple effect absorption cycle has the highest COP, followed by the hybrid GAX and standard GAX cycles. However, the vapor absorption cycle with a large temperature glide has the lowest COP.

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