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Review Article

Performance enhancement of absorption refrigeration systems: An overview

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ABSTRACT

The introduction of absorption refrigeration technology addressed several significant concerns in the domain of energy crisis, rising cost of fossil fuel, and ecological challenges arising due to the excess use of traditional compression refrigeration systems. ARS (absorption refrigeration system) is gaining popularity as a result of benefits such as the use of low-grade heat sources and environmentally acceptable low-cost working fluid pairs. However, two significant hurdles to commercial success for this technology are the often too big size of the refrigeration system and the poor performance of the system. Numerous studies have been conducted in an attempt to discover methods for improving the COP (coefficient of performance) of ARS in order to get these systems more competitive in comparison to the conventional compression refrigeration systems. The goal of this article is to perform a review of the literature on different methods used to enhance the COP of ARSs based on cycle layout modification and working pair selection as they are the promising solutions for the enhancement of the performance of ARSs. The futuristic aspect of this technology includes the introduction of new working pairs with no corrosion to the system components, including nanoparticles to increase heat transfer rate while reducing the cost of the system. Heat recovery methods should be introduced and the efficient design of various components especially the generator and absorber are to be addressed. This technology could be combined with other refrigeration technologies while utilizing the waste heat to further improve the efficiency of ARSs.

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INTRODUCTION

In recent decades the need for space cooling and refrigeration devices have increased dramatically to meet a variety of storage and comfort requirements. Conventional vapour compression refrigeration systems (VCRS) use around 20 percent of all the energy produced globally, corresponding to the International Institute of Refrigeration (IIR) report. Over the next several years, the utilization rate is expected to further increase to 50% that of residential buildings and commercial hubs [1]. The rapid increase in energy usage for such refrigeration devices has put tremendous strain on conventional sources of energy, implying the phasing

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out of fossil fuels shortly will be unless an urgent action is taken. Furthermore, rising energy demand has raised the costs, stressing the need to increase the conservation of the current energy resources by lowering the rate of utilizing energy or finding new energy sources. The use of renewable energy to run refrigeration systems (e.g., waste heat from industrial operations, IC engines, wind, and solar energy) has become a more attractive area of study in recent years due to their long-term and plentiful accessibility [2–5]. The huge consumption of energy required to operate the compressors in traditional VCRS emits significant amounts of gases responsible for global warming, leading to a variety of environmental/ecological problems. Despite the high performance of VCRS, absorption technology has low performance, but it could be powered by low grade thermal energy. They utilize ecologically sustainable refrigerants and rejection of heat in absorber and condenser takes place. These characteristics of ARSs make them ideal for driving a desalination system and to produce fresh water [6]. Furthermore, conventional refrigerants such as chlorofluorocarbons (CFCs), hydrocarbons (HCs) and hydrochlorofluorocarbons (HCFCs) used in conventional VCRS are causes depletion of ozone layer and contributes to global warming [7,8]. Several communities worldwide have taken considerable endeavors to preserve the environment and ozone layer depletion, that includes the limiting use of chlorofluorocarbons (CFCs) that have chlorine content in it and the hydrofluorocarbons (HCFCs) that releases greenhouse gases, under the influence of Montreal (1987) and Kyoto (1997) protocols. Regardless of these efforts, NASA [9] estimates that the ozone hole has grown from approximately 2.4 x 107 km^2 in 1994 to about 2.83 x 107 km^2. The European Commission (EC) passed a resolution in October 2000 prohibiting the use of all HCFCs by 2015 [4,10]. According to a study by a climate change institution, there is a rise in average temperature of world by 0.6 degrees since the turn of the century, and this rise in temperature is projected to climb by 1.4–4.5°C, by the end of 2100 if there is no change in the emissions of greenhouse gases [11].

Due to the ecological/environmental issues created by traditional VCRS, there is a great demand to replace conventional refrigeration systems with the alternative refrigeration technologies which are eco-friendly in nature [12,13]. The study into the utilization of waste heat and renewable energy has resulted in the development of innovative refrigeration systems. These methods not only reduce greenhouse gas emissions, but they also save other energy sources. This study deals with the comprehensive overview of absorption refrigeration systems, methods to enhance its performance based on cycle layout modification, working pair selection and its flow pattern considering various aspects and working ranges. This study encourages the use the eco-friendly refrigerants to produce refrigeration and air conditioning without having harmful impact on the environment and make an efficient use of the resources to enhance the system performance. Further, the future aspect of this technology may use the new working pairs with nanoparticles, compact heat exchangers and combining other alternative refrigeration systems to improve overall efficiency of the system.

Absorption Refrigeration Technology

The absorption refrigeration technology is a potential alternative to conventional VCRS that has drew the attention of scientists and engineers in recent years. The absorption refrigeration technology is a thermally powered refrigeration technique that uses heat energy which can be taken from any low-grade energy reservoir or solar energy to provide cooling. such as the exhaust of IC engine [14]. The generator, pump, absorber, solution heat exchanger, condenser, expansion valves and evaporator are the various components combined to form an ARS, as illustrated in Figure 1. This system utilizes an absorber-generator assembly to rise and transport the weak solution via a pump and thermally compressed the working fluid when heat is delivered to the generator, instead of utilising an electrically powered compressor. When the refrigerant flows through the evaporator, it vaporises itself while extracting thermal energy from the region desired to get cooled [15,16]. Further, the saturated vapour subsequently entered the absorber to get absorbed in the weak solution, which was relatively colder than the ambient. The diluted /weak solution fed to the generator via solution heat exchanger (SHX), at this stage the refrigerant is thermally desorbed when heat is provided to it, the refrigerant vapour further rejects heat in the condenser and gets condensed. After that, the condensed refrigerant in liquid state reduced to a lower pressure via throttling valve and subsequently entered the evaporator to get vaporized further and provide cooling. During the generation procedure, the strong solution from the generator entered SHX and further reduces its pressure via pressure reducing valve and enters the absorber. The saturated vapour of refrigerant fluid exiting the evaporator was absorbed in the solution available which is weak in refrigerant, in the absorber component and the cycle is continued [17,18].

The following are some of the benefits of absorption systems:

- Low-grade heat energy sources like I.C. engine exhaust, industrial thermal waste and renewable energy sources such as solar energy, may be utilized to operate absorption refrigeration systems. As a result, the system is suitable for decreasing CO_2 emissions and offers a lot of potential for energy savings.
- Environmentally sustainable refrigerants like water or ammonia are used in absorption refrigeration systems, minimizing their effect on the depletion ozone layer and greenhouse emissions.
- As the ARS with no moving parts, the operation of these systems is quiet, leading to easy maintenance and low-cost operation.
- Absorption refrigeration systems have a long-life expectancy of 20–30 years.

Despite these advantages, ARSs are less efficient than conventional VCRSs in terms of energy use. Figure 2 depicts the absorption refrigeration technology's major benefits and drawbacks.

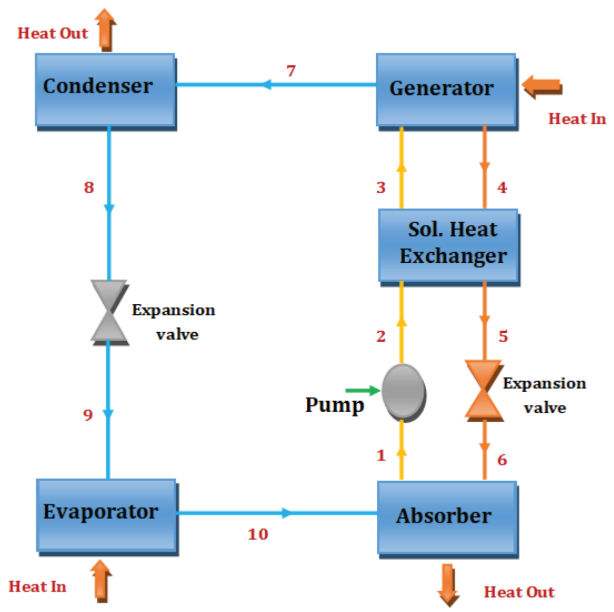

Figure 1. Schematic of SE-ARS.

A lot of work has been undertaken with various options in mind to improve the coefficient of performance (COP) and refrigeration capacity to overcome major challenges and boost the usage of ARS technology.

The coefficient of performance (COP) that is used to assess the effectiveness of the absorption refrigeration systems is given by:

$$COP = \frac{Quantity\ of\ cooling\ produced}{Quantity\ of\ heat\ supplied} \quad (1)$$

The current study is an effort to provide the review of various design and construction of ARSs, keeping in mind to enhance the performance and utilization of the absorption cooling systems.

where k_{medium} is the absorption index of the medium which is wavelength dependent.

The total extinction coefficient of a nanosuspension when combined is as given below:

$$\sigma_{total} = \sigma_{ext,p} + \sigma_{ext,m} \quad (2)$$

Improvement of Absorption Systems Based on the Cycle Layout

This section refers to the enhancement and utilization of absorption refrigeration system based on its cycle design. Table 1. shows the advantages of various methods/configurations of ARSs. Various designs of absorption refrigeration systems have been discussed for different operations conditions and utilization, it includes half effect, single effect, double effect and triple effect ARSs. An overview on a variety of configuration for ARSs is listed in Table 2.

Single-effect and half-effect cycles

The basic cycle layout of an ARS is single effect absorption refrigeration system (SE-ARS). A number of experimental, analytical, and computational studies had been conducted to evaluate the performance of SEARS with various working fluid pairings under various operational conditions [19,20]. Several successful methods have been utilized to improve the COP of SE-ARSs, that includes the adjustment of operating conditions and choice of new working fluid pairs having superior thermodynamic characteristics than traditional one [21,22].

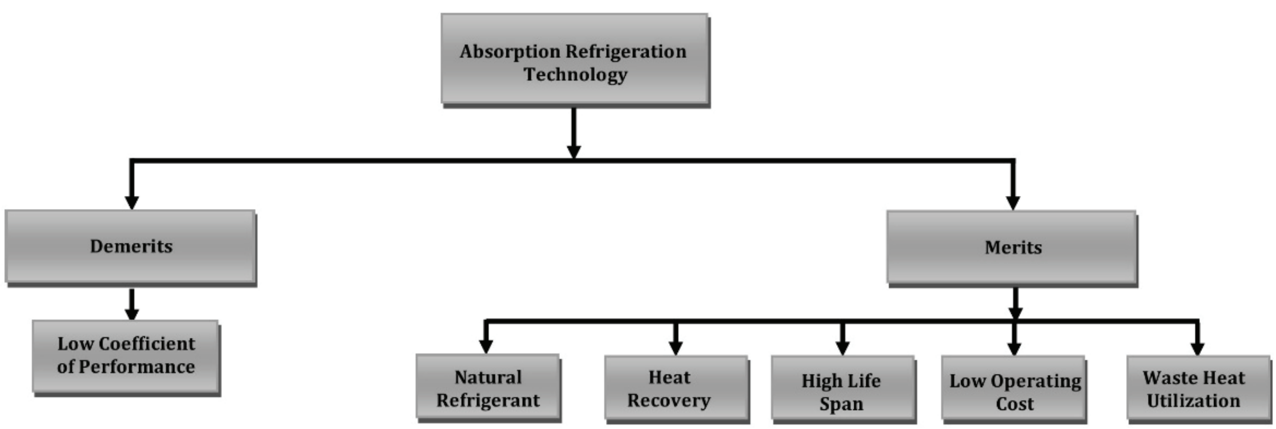

Figure 2. Merits and demerits of absorption refrigeration technology.

Despite this, the performance of SE-ARS is low. In order to improve the energy efficiency of the SE-ARS, tc-CO_2 compression refrigeration system was coupled to utilize the waste heat rejecting in the gas cooler of the system to run ARS [23] in some of the research papers. Various other combinations of alternative refrigeration technologies which can operate on waste heat such as absorption and adsorption refrigeration techniques were combined to improve the performance of ARSs [24], but the complexity of the system increases [25]. Bellos et al. [26] presented their research on single-stage absorption system the operated by parabolic trough collector. SE-ARS uses an NH_3/water as the working pair to provide refrigeration in the -35°C to 5°C temperature range. There is an optimal temperature of generator for which the performance was maximum under the specific operating conditions. The annual system coefficient of performance for cooling output at -25°C and 40°C as the heat rejection temperature was found to be 0.255, the annual exergy efficiency is 4.87 percent, and payback time was ten years. When there is low temperature thermal energy is available to run the machine, the performance of SE-ARS decreases dramatically. To overcome this difficulty, a half-effect absorption refrigeration system (HE-ARS) [27]. Figure 3 was suggested to drive this system with a low temperature thermal energy while the performance of half effect cycle is approximately half as that of the SE-ARS [28]. The HE-ARS combines a SE cycle with a double-lift structure that may operate with lower-quality thermal sources at temperatures as low as 55°C [29]. Verma et al. [30] provided a thermodynamic study of a HE-ARS using the working fluid pair as LiBr-H_2O. The HE-ARS was powered by the flat plate collector's low-temperature hot water. A cooling load of about 25 kW has been estimated for office building. At the optimal generating temperature, the collector area was reduced. The temperature at which two generators operate optimally was determined to be 80 °C. The highest COP, and the exergy efficiency, at the optimal generator temperature was 0.416 and 7.36 percent, respectively. A new half effect absorption system operated with low grade heat was proposed by Xiaohui et al., [31]. At the high-pressure stage, the H_2O-LiCl pair with higher vapour pressure is utilised, whereas the H_2O-LiBr pair with lower vapour pressure is used in the low-pressure stage [32]. The pressure at the intermediate level was the crucial parameter for system performance; it should be chosen to guarantee a reduced circulation ratio during the cycle's lower-pressure portion [33,34].

Double-effect cycle

There has been a lot of work put into making ARSs more competitive with traditional VCRSs. Since, single-effect absorption systems have a poor performance, double-effect absorption refrigeration system (DE-ARS) have

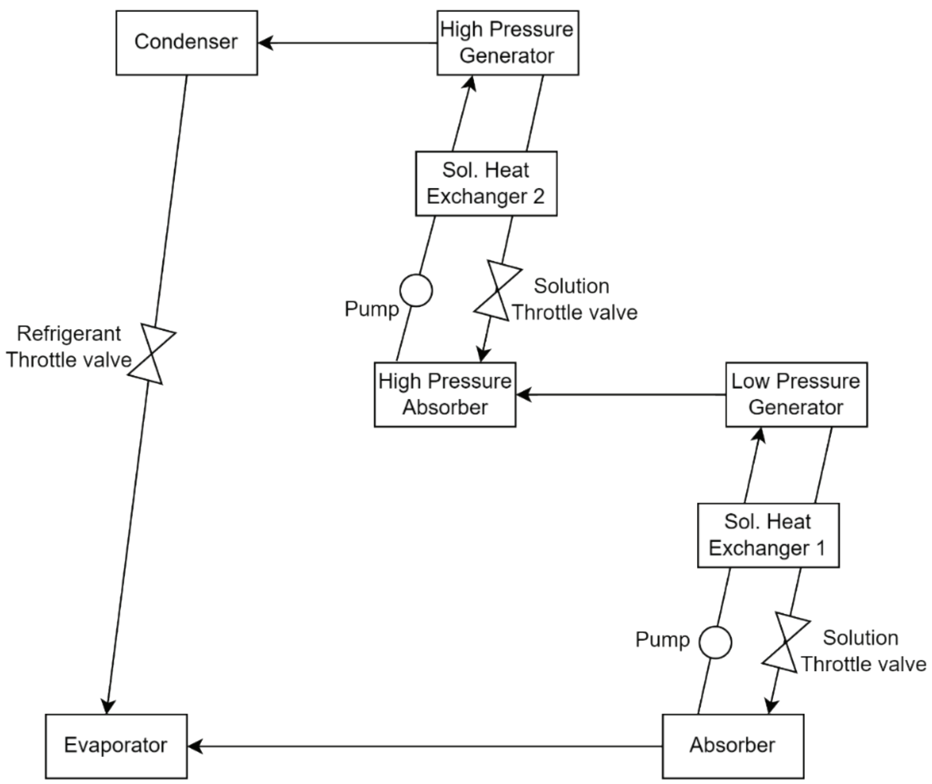

Figure 3. Schematic of half effect ARS.

been suggested for better performance [35,36]. The generator temperature in such systems is greater than that considered necessary to run a SE-ARS. Gomri [37] performed a comparison study between SE-ARS and DE-ARS. The performance of the later cycle was twofold to that of the former cycle, according to the findings. To assess the performance efficiency of a single-effect cycle and a double-effect cycle with H_2O-liBr as the working fluid in a series mode flowing of the solution, Arora and Kaushik [38] created a computer model/program. The impact of operational conditions and a variety of parameters on system performance was studied. The performance of the DE-ARS was found to be 60–70% more when compared to the SE-ARS, according to the findings. Furthermore, the maximum COP was achieved at a low generator temperature, which was achieved by diminishing the temperatures of absorber and condenser while raising the evaporator temperature and solution heat exchanger efficiency. Colorado [39] reported the theoretical findings of an improved exergy analysis of a series flow DE-ARS. The advanced exergy study showed that the absorber is the component that is having highest destruction of exergy in the system. The high-pressure generator's design and manufacturing have the most opportunity for improvement since 67.47 percent of endogenous exergy degradation is avoidable. The performance of different configurations of ARSs using NH_3-$LiNO_3$ [40] and H_2O-LiBr [41] solutions were compared by Domnguez-Inzunza and colleagues. Crystallization and corrosion are the two important issues faced in the design and analysis of a DE-ARSs, leading to poor performance and choking of the complete system. Researchers have looked at two key aspects, like area available for heat transfer and the crystallization of solution, contributes significantly in the design of DE-ARSs [42,43]. According to the findings, lowering the circulation ratio of solution and enhancing the ratio of heat-recovery improves the system overall performance and avoid crystallization while having reduction in the total heat-transfer area. Li and Liu [44] conducted a theoretical study to determine the proper heat to load ratio intended for the generator in a DE-ARS using a LiBr-H_2O as working pair, as an crucial factor that significantly reduced the risk of crystallization and influenced the system performance. In DE-ARSs, there are the two basic circulation strategies regarding the flow of solution (strong/weak) in the generator-absorber assembly, known as the series and parallel flow mode as depicted in Figure 4.

The comparison of parallel and series flow schemes in a DE-ARS using a combination of LiBr-H_2O as working pair was conducted by Grossman et al. [45], to see how the two flow schemes affected performance of the system. The system performed better in parallel flow than the other configurations, according to the findings. Furthermore, in the parallel flow configuration, the operating conditions occurred far away from LiBr-H2O working fluid crystallization line. The way the solution is spread throughout the different generators is the distinction between series and parallel flow configurations. The solution is pumped straight from the absorber to the high temperature generator in the series flow, whereas it is distributed between the two generators in the parallel flow. The solution pumped from the absorber is separated at the outlet of the low-pressure solution heat exchanger and fed separately to the high temperature and low temperature generators in the parallel flow cycle. The solution distribution ratio is an important

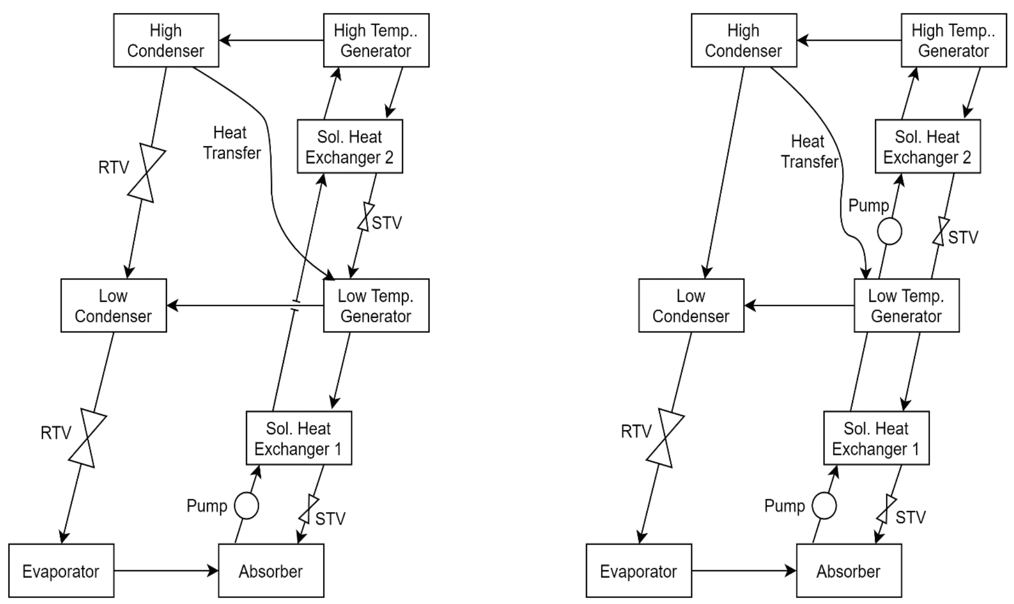

Figure 4. Schematic of double effect ARS (a) Series Flow Mode (b) Parallel Flow Mode.

parameter in parallel flow mode and is defined as the ratio of solution entering the high temperature generator to the solution leaving the solution pump. In comparison to a series flow system, the performance of a parallel flow system is more sensitive to changes in evaporator temperature and less susceptible to the changes in condenser and absorber temperature. In general, the COPs are found higher in parallel flow than that in series flow configurations [46,47].

Yang et al. [48] developed a unique high-performance H_2O-LiBr based DE-ARS for tri-generation applications that utilizes a variety of heat sources, including high temperature steam and hot water. There were five alternative flow configurations simulated, that included series, reverse, revised series, parallel, and revised reverse flow patterns. The cycle efficiency was evaluated on the basis of generator sequence and the quantity and location of the extra heat exchangers. The COPs of the configurations with revised serial and reverse pattern were generally greater than that of serial and reverse configurations schemes, according to the findings. Furthermore, the parallel cycle was found to be superior to other systems in terms of COP. Furthermore, the ratio of heat source had a major influence in determining the most efficient cycle, according to the authors. For the ratio of heat source to be 0.7, the revised reverse cycle was found to be the most appropriate cycle, whereas the parallel cycle had the maximum value of COP when the ratio of heat input was greater than 0.71. A comparative study was performed to assess the effectiveness of a H_2O-LiBr solution-based DE-ARS. The three types of configurations were investigated: parallel, reverse parallel, and series. The system with the parallel flow configuration was found to have the greatest performance among the different flow types [49]. Chahartaghi et al. [50] presented a new LiBr-H_2O working pair DE-ARS with a heat exchanger for recovery of heat. The study looked at two flow configurations, including series and parallel flow systems. The findings showed that when the temperature of generator was less than 150°C, the series design offered a higher performance than that of the parallel flow configuration. When the input temperature to the generator was greater than 150 °C, however, the parallel system was shown to perform better than the series design.

Triple-effect or multi-stage cycles

The triple effect absorption refrigeration system (TE-ARS) was created to retrieve more energy and therefore improve the COP, despite the fact that they required the heat source temperature to be greater than that of a DE-ARS. In Figure 5 (a-b), the TE-ARS in series and parallel flow mode are shown respectively.

The triple effect cycle, in contrast to the DE cycle, includes an added assembly of high-temperature generator along with a condenser, offering three generators and condensers to the whole system. As a consequence, this cycle design permits for higher energy recovery, which boosts the performance of the system [51]. Gebreslassie et al. [52] investigated the influence on the performance for different flow configurations of a triple-effect LiBr-H2O ARS and other configurations, including series and parallel flow arrangements on the basis of exergy analysis. It was found that the parallel flow mode of the triple effect ARS, had the highest COP. However, higher heat source temperatures were utilized in the generator of these systems, the usage of LiBr-H_2O in the TE-ARS may produce the problem of corrosion.

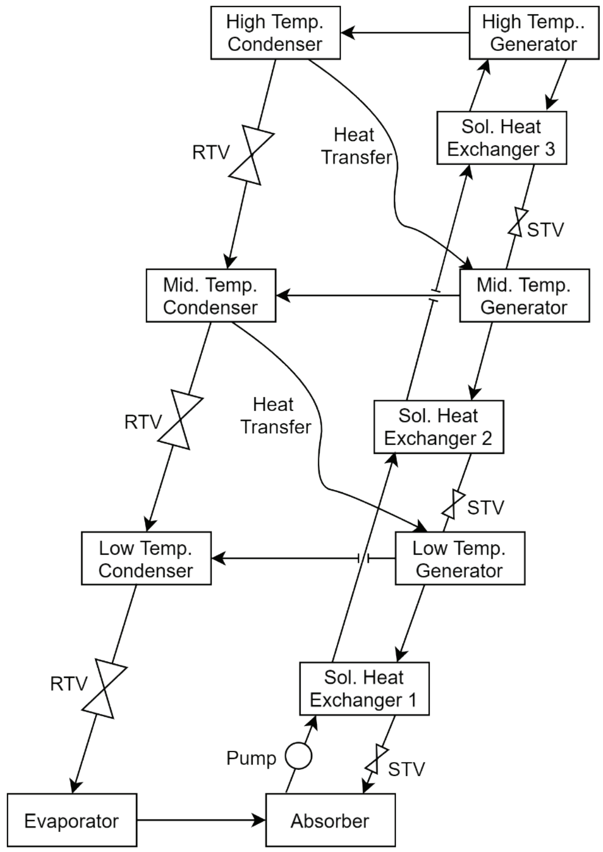

Figure 5. Schematic of triple effect ARS (a) Series Flow Mode.

Figure 6 indicates the comparison of COP for various absorption cycle configurations based on its cycle design. According to this statistic, the increase in the number of generators improves the COP of the cycle appreciably. The triple-effect cycle achieving the maximum COP. These cycles, however, require high heat source temperatures in order to function [53]. A half-effect cycle, on the other hand, is intended to function at low quality heat source temperatures (60 to 80°C) while producing a low COP, but it has a greater number of components. The SE cycle is the simplest and less costly among all of the investigated designs since it has lesser components compared to other configurations. Furthermore, the SE ARS can function at medium heat source temperatures (80 to 100°C). The higher values COP could be obtained

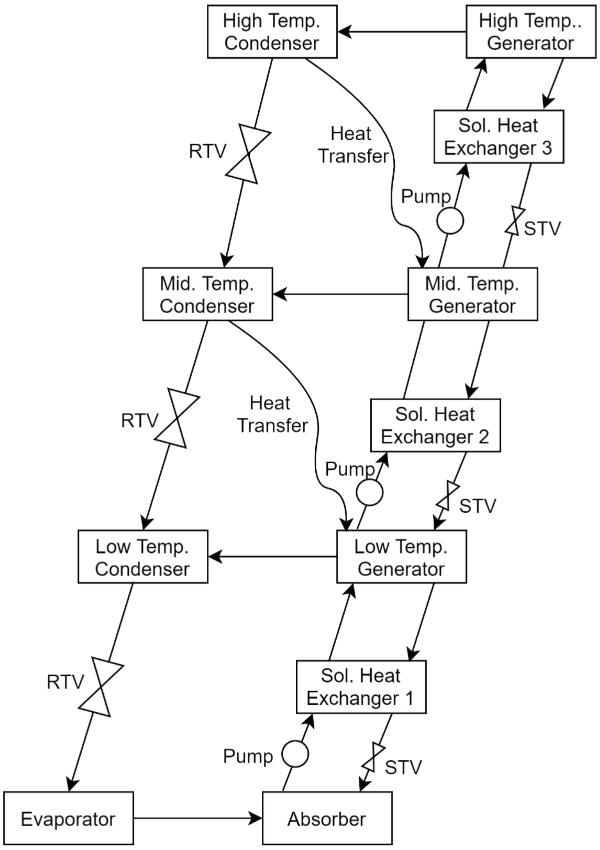

Figure 5. Schematic of triple effect ARS (b) Parallel Flow Mode.

in parallel flow mode as compared to that of the series flow mode in the double-effect and triple-effect cycles.

Working pair selection

The absorption refrigeration systems performance is significantly affected by the thermodynamic properties of the working fluid, so choosing the right absorbent and absorbate (refrigerant) is critical. The right choice is determined by the heat source temperature, the refrigeration system desired characteristics, the properties of the working pair components and their affinity. When selecting a working fluid pair for an absorption cooling system, the following factors must be taken into account [57]:

- For the refrigerant inside the absorbent, should have large latent heat of vaporization.
- The mixing of refrigerant and the absorbent is an exothermic reaction, it should have low heat of mixing.
- Low viscosity, low boiling point, high miscibility, diffusive coefficient, and conductivity are all desirable thermodynamic properties.
- There should be no crystallization at any stage of operation of the system.
- The working pair should be environmentally friendly, chemical stable, easily available and it should be cost effective.

In ARSs, due to the favourable thermodynamic properties, LiBr-H_2O and H_2O-NH_3 solutions are the very popular working fluid pairings employed. The NH_3-H_2O based chillers are commonly utilized for domestic and small industrial refrigeration purposes requiring lower refrigerating temperatures, whereas the LiBr-H2O based chillers are commonly utilized for large industrial cooling applications requiring medium cooling temperatures.

According to scientists in [58,59], the thermodynamic properties for the mixture of LiBr-H_2O, are the important reasons due to which it cannot provide cooling below 0°C. For the same evaporation temperature, Kim and Ferreira [60] found that the working pair utilizing LiBr-H_2O has more system performance than that with using H_2O-NH_3. The performance of a single-effect ARS using two working

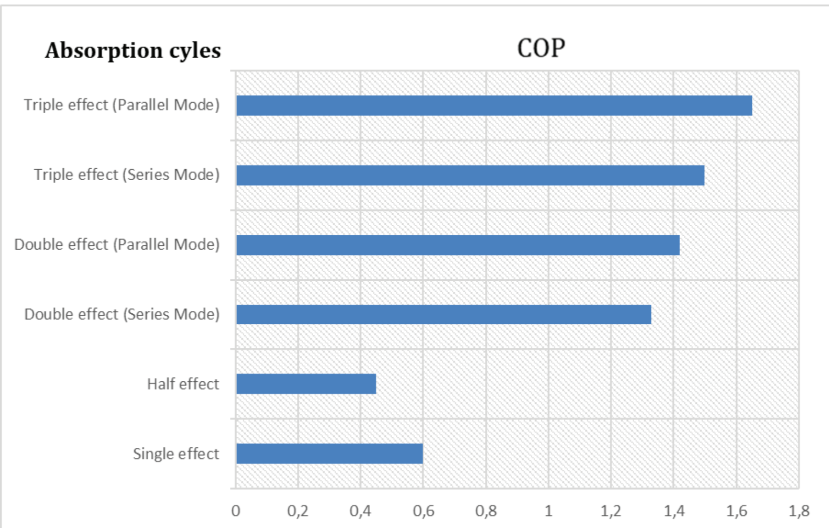

Figure 6. COP comparison for different ARSs.

Table 1. Advantages of different methods/configurations used for ARSs.

Method/Configuration of ARS	Advantages
Single effect	Simple configuration with less components and easy operation with moderate range of generator temperature (100 to 110°C).
Half effect	Low values of heat source temperatures in the generator (60 to 80°C) are required.
Double effect	In comparison to SE, the COP of the DE configuration is increased by 60–70%, although higher generator temperature.
Triple effect	Higher performance compared to that of DE systems when high heat source temperature (210 to 250°C) is available
Series flow	Simple configuration where solution is pumped to high temperature generator in a single stage.
Parallel flow	Parallel mode performance is superior compared to series mode.

Table 2. Brief literature on a variety of configuration for ARSs.

Type of ARS	Working pair	Working Temperatures (°C)	COP	Remarks	Ref.
Single effect	LiBr-H_2O	Ta = 30 to 45 (°C), Tc = 30 to 45 Tg = 80 to 105 Te = 4 to 10	0.57 – 0.82	The effect of SHX is more than that of refrigerant heat exchanger	[20]
Single effect	LiBr-H_2O	Ta = 17 to 48 (°C), Tc = 17 to 48 Tg = 58.5 to 110 Te = 0 to 30	0.15 – 0.75	Every assumption and functioning parameter were stated and justified.	[19]
Single effect	LiCl-H_2O LiBr -H_2O	Ta = 31 to 37 (°C), Tc = 31 to 37 Tg = 55 to 90 Te = 1 to 11	0.12 – 0.38	The suggested system has a higher COP than the standard LiBr-H_2O cycle. The series mode was preferred because it allowed for operation with a low-grade heat source.	[31]
Half effect Single effect Double effect	LiBr -H_2O	Ta = 25 to 50 (°C), Tc = 25 to 50 Tg = 55 to 165 Te = 2 to 19	0.32 – 0.45 0.65 – 0.92 1.10 – 1.75	The double effect produced the highest COP, whereas the half effect needed low values of heat source temperatures in the generator (from 60 to 80°C).	[41]
Single effect Double effect	LiBr -H_2O	Ta = 25 to 45 (°C), Tc = 28 to 36 Tg = 120 to 150 Te = 5 to 10	0.65 – 0.75 1.15 – 1.30	In comparison to SE, the COP of the DE configuration is increased by 60–70%.	[38]
Double effect (Series flow) Double effect (Parallel flow)	LiBr -H_2O	Ta = 30 to 45 (°C), Tc = 30 to 45 Tg = 85 to 170 Te = 2 to 11	1.17 – 1.42 1.32 – 1.50	Parallel mode performance was superior to series mode performance.	[54]
Double effect	LiBr -H_2O	Ta = 33 to 42 (°C), Tc = 32 to 42 Tg = 107 to 207 Te = 4 to 10	0.9 – 1.30	In detailed analysis of double effect system is given with the effect of various parameters were given	[49]
Double effect (Series flow)	LiBr -H_2O	Ta = 25 to 40 (°C), Tc = 30 to 45 Tg = 85 to 170 Te = 2.5 to 10	0.9 – 1.40	Design conditions for optimum performance were suggested	[55]
Double effect	LiBr -H_2O	Ta = 20 to 35 (°C), Tc = 20 to 35 Tg = 130 to 200 Te = 2.5 to 10	0.6 – 1.19	The COP in series flow arrangement was high when Tg < 150°C, on the other hand but it is superior in parallel flow when Tg > 150°C.	[50]
Single effect Double effect Triple effect	LiBr -H_2O	Ta = 33 to 39 (°C), Tc = 33 to 39 Tg = 60 to 225 Te = 10 to 15	0.73 – 0.79 1.22 – 1.42 1.62 – 1.90	There was an optimal generator temperature for specific temperatures of evaporator and condenser, corresponds to maximum COP of the system	[56]

pairs: LiCl-H_2O and LiBr-H_2O was investigated by Patel et al. [61], for similar operating parameters. The results showed that the former working pair had a significant improvement of system performance than the latter one.

Won and Lee [62], investigated a DE-ARS using LiCl-H_2O as the working fluid and made a comparison of it to the system using the standard LiBr-H_2O mixture. The end result revealed that the H_2O-LiCl working pair had a better performance in comparison to the system with standard H_2O-LiBr. Kaushik and Kumar [63], investigated the effect of the working fluid pairs: NH_3-H_2O and NH_3-$LiNO_3$ on the COP in a two-stage ARS. The outcomes indicated that the cycle having NH_3-$LiNO_3$ solution produced a higher COP than the cycle with H_2O-NH_3. A theoretical study has been carried out by Karamangil et al. [64], to examine the effect of three different binary working pairs as NH_3-H_2O, NH_3-$LiNO_3$ and H_2O-LiBr, on the performance based on energy analysis for a single-effect ARS. The system with H_2O–LiBr working pair performed the best among the configurations studied. Though, due to the crystallization issue, the system could only operate in a restricted range of heat source (generating) temperatures. When the system tended to operate at the heat source temperature that is less than 75 °C, NH_3–$LiNO_3$ was the most suited option among the three working pairs. Cai et al. [65], explored the performance of an NH_3-NaSCN-based double effect ARS. For the variation of the evaporating temperature from -10°C to 5°C, the COP of the system rises by 10 to 15%, in comparison to the system using NH3-LiNO3 as a working fluid. Although, for low refrigerating temperature like -15°C, the system using NH_3-$LiNO_3$ performs better than that of the system utilizing NH_3-NaSCN as the working pair. An experimental study has been performed to examine the efficiency of a single-effect absorption chiller by Cai et al. [66]. Two types of working fluids were used: NH_3–$LiNO_3$ and NH_3–NaSCN. The performance of the configurations with NH_3–NaSCN was found to be higher than that with NH_3–$LiNO_3$ for similar operating conditions, the COP values for the two pairs were varied between 0.20 and 0.35. The experimental results attained in this study are valuable in developing a improved ARS using ammonia based salts. Cerazo et al. [67], investigated a single-effect ARS using plate heat exchanger with bubble absorber with NH_3-$LiNO_3$, NH_3-NaSCN, and NH_3-H_2O as the working pairs. Their simulation results demonstrated that the NH_3-$LiNO_3$ performs the best, while the NH_3-NaSCN has better performance to that of conventional NH_3-H_2O systems for similar working conditions. For the generator temperature of 120°C, the COP of the three working pairs is 0.61, 0.55 and 0.49 respectively. A theoretical analysis has been done on a DE absorption refrigeration cycle using a tertiary solution of H_2O-LiBr-LiSCN and comparison had been made for the COP of the system with LiBr -H_2O and LiCl-H_2O based ARS. The scientists stated that the cycle with H_2O-LiBr-LiScN solution as a working pair performed better compared to H_2O-LiBr and H_2O-LiCl based configurations individually [68]. The results showed that the system COP improved by 3% over the system having H_2O-LiBr as the working pair. Koo et al. [69], found that the tertiary solution of H_2O-LiBr-$LiNO_3$ performed better and was less corrosive to the system compared to the conventional binary solution of H_2O-LiBr. Moreno-Quintanar et al. [70], investigated an ARS powered thermally by solar energy, that uses a tertiary solution of NH_3-$LiNO_3$-H_2O and a binary solution of NH_3-$LiNO_3$ as the working fluid pairings. The outcomes depicted that using a tertiary mixture enhanced system performance by 24% as this configuration was powered by low-grade thermal energy sources. Steiu et al. [71], carried out a simulation study using experimental data for an NH_3-H_2O based ARS. The study showed that the addition of NaOH to ammonia/water enhances ammonia separation in the generator and decreases the operating temperature in generator. The system COP has risen by 20% in comparison to a standard ammonia-water solution under similar operating conditions.

Figure 7 depicts the influence of a variety of working fluid pairings on the performance improvement of the absorption systems as per the literature available. It can be seen that the most familiar working pairs employed in absorption cooling systems are LiBr-H_2O and NH_3-H_2O. The usage of LiBr-H_2O solution in this system improves the performance, even though the system may only work in a limited range of heat source (generating) temperatures due to the crystallization issue. Thus, the LiBr-H_2O working fluid pair is mostly used in large industrial cooling purposes requiring medium range of generator temperatures, while the refrigeration temperatures should be above 0°C for steady state operation. The NH_3-H_2O solution, on the other hand, is commonly used in domestic and light industrial refrigeration purposes if low source temperatures are available, while the refrigeration temperatures can go below 0°C with proper functioning of the system.

If the availability of heat source (generator) temperature was less than 75°C, among the three-ammonia based working pairs, the NH_3-$LiNO_3$ yielded the better COP. If a high-temperature heat reservoir (more than 80°C) was available, the NH_3-NaSCN solution performed best among the three pairs. In order to enhance the performance of NH_3 based binary fluids utilized in the ARSs, the ternary fluids were adopted. The addition of NaOH particles in NH_3-H_2O solution has been done to improve the COP, resulting in a 20% increase in system performance. In this respect, the addition of $LiNO_3$ to both NH_3-H_2O and H_2O-LiBr binary working fluids was an effective attempt to enhance system performance. In comparison to H_2O-LiBr, a higher COP was obtained by using a tertiary solution of H_2O-LiBr-$LiNO_3$ with less corrosion to the system. Furthermore, adopting NH_3-LiBr-$LiNO_3$ as a tertiary solution enhanced the system COP significantly in comparison to the standard working pair of NH_3-H_2O.

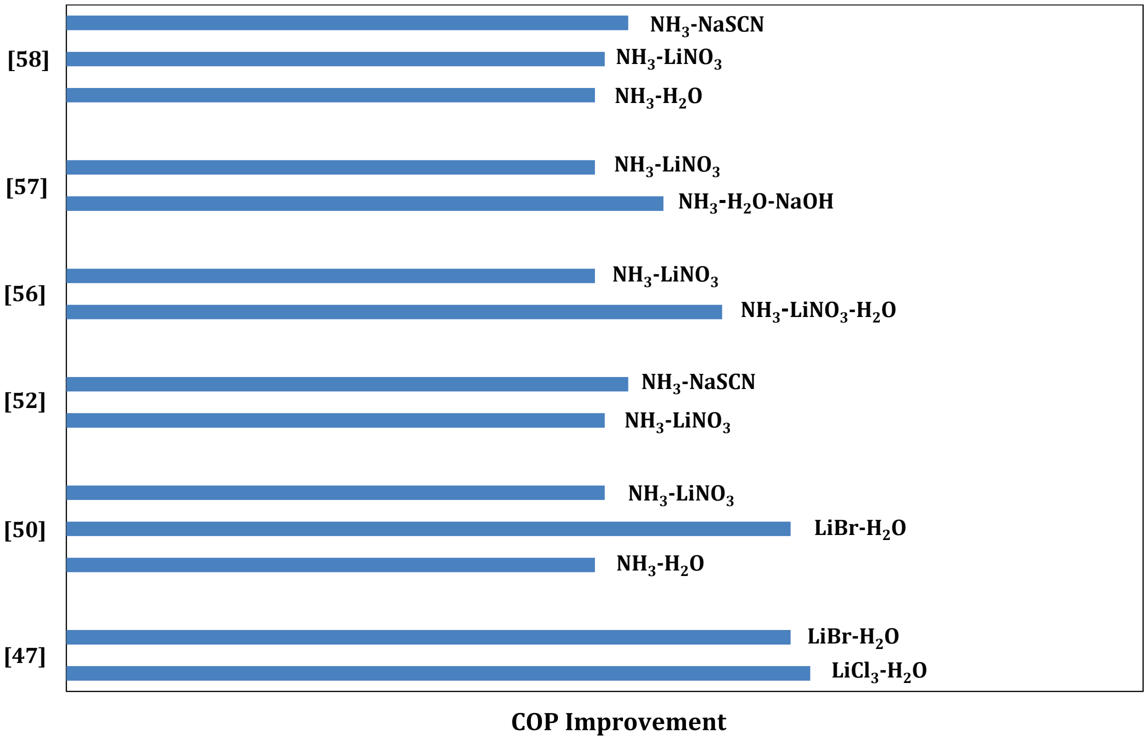

Figure 7. COP of ARSs with a variety of working pairs.

An overview of discussed working pairs in the absorption systems is offered in Table 3, to allow for a clearer comparison of several working pairs utilized in ARSs. The table shows that water is the primary refrigerant in the majority of the working solutions because of its numerous merits, including ecofriendly and readily available.

Present Developments and Futuristic Aspects of ARS

The present analysis of numerous studies conducted on different designs of the ARSs showed that the efforts have been made to increase the performance, its reliability and create new uses of this technology. Despite the significant advances in the system performance, more study

Table 3. Brief characteristics of ARSs with various working fluids

Type of ARS	Working fluid pairs	Remarks	Reference
Single effect	LiCl-H_2O, and LiBr-H_2O	The solution of LiCl-H_2O performs better than LiBr-H_2O	[61]
Double effect	LiCl-H_2O, and LiBr-H_2O	The solution of LiCl-H_2O performs better than LiBr-H_2O	[62]
Single effect	NH_3-$LiNO_3$ and NH_3-NaSCN	The solution of NH_3-NaSCN improves performs over NH_3-$LiNO_3$ solution	[66]
Double effect (Series flow)	NH_3- NaSCN, NH_3-$LiNO_3$	The solution of NH_3-NaSCN performs better compared the system using NH_3-$LiNO_3$	[65]
Half effect	NH_3-$LiNO_3$, NH_3-H_2O	The solution of NH_3-$LiNO_3$, performs better than the conventional NH_3-H_2O solution, also it can use lower generator temperatures	[63]
Single effect	NH_3-H_2O, NH_3-LiNO3, NH_3-NaSCN	The solution of NH_3-NaSCN improves performs over the use of NH_3-$LiNO_3$ and NH_3-H_2O solution	[72]
Single effect	NH_3-H_2O-NaOH	Lower generator temperature, better performance, better separation of NH_3 in generator	[71]
Double effect	H_2O-LiBr-LiScN, LiCl-H_2O, and LiBr-H_2O	The tertiary solution of H_2O-LiBr-LiScN performs better than LiBr-H_2O and LiCl-H_2O	[68]
Double effect (Series flow)	H_2O-LiBr-$LiNO_3$-LiI-LiCl	Lower generator temperature, higher performance without crystallization	[73]

is needed in the area of absorption systems which are as follows:

- to reduce the system's cost, new pairs of working fluid with no risk of corrosion should be developed.
- adopting sophisticated heat recovery methods to improve overall heat recovery while avoiding design complexity by embedding sub-components into the basic cycle.
- designing of efficient generators, absorbers and solution heat exchangers for novel ARS.
- increasing the use of renewable energy sources or waste heat from industries for absorption cooling technologies.
- Combining the refrigeration technologies which operates on waste heat with environmentally friendly refrigerants.

CONCLUSIONS

The important options to develop methods for improving absorption refrigeration system performance were examined. This includes changes to the cycle's design. The following is a summary of the research findings:

- Absorption cycles of several kinds have been designed, each with a distinct number of stages and effects. The SEARS is the benchmark (basic) absorption cycle against which the performance of newly designed absorption cycles was measured, according to the literature.
- When there is availability of thermal energy sources having high-temperature levels, double effect cooling cycles have been suggested to enhance the system performance.
- The triple-effect absorption cycle provides the best energy performance, followed by DE-ARS and SE-ARS, but with more heat exchangers and further cost.
- For multi-effect ARS, particularly the triple-effect (TE) system, have surpassed SE and DE ARSs in terms of performance. Even though a rise in the number of effects does not always favors better performance of the system as the average cost and its complexity of the systems increases. Furthermore, to drive multi-effect cycles, thermal energy source with relatively high temperature is needed.
- When the temperature of the heat reservoir is very low, the half effect cycle has been advised. This cycle, on the other hand, have coefficient of performance approximately half as that of the single-effect cycles.
- Although there were various combinations of working fluid pairs, including tertiary and quaternary pair solutions, have been developed in order to improve the energy performance of the absorption systems for specialized applications, the two major pairings of working fluid, H_2O-NH_3 and LiBr-H_2O, had been the utmost choice in general-purpose ARS.

NOMENCLATURE

ARS	Absorption Refrigeration System
SE	Single Effect
HE	half effect
DE	double effect
TE	triple effect
COP	coefficient of performance
VCRS	vapour compression refrigeration system
HC	hydrocarbons
CFCs	chlorofluorocarbons
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
IIR	International Institute of Refrigeration
NASA	National Aeronautics and Space Administration
SHX	solution heat exchanger
RTV	refrigerant throttle valve
STV	solution throttle valve

Working pairs

$LiBr/H_2O$	lithium bromide/water solution
NH_3	ammonia
LiCl	lithium chloride
LiSCN	lithium thiocyanate
LiI	lithium iodide
NaSCN	sodium thiocyanate
tc – CO_2	trans-critical carbon dioxide

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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