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Review

Hybrid Ejector-Absorption Refrigeration Systems: A Review

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Abstract: Absorption Refrigeration Systems (ARS) are potential alternatives to direct expansion (DX) refrigeration systems. This review focused on the incorporation of an ejector into absorption refrigeration cycles to constitute Hybrid Ejector-Absorption Refrigeration Systems (HEARS). The ejector adds several advantages to the absorption refrigeration systems depending on its location in the cycle. The two prevalent configurations of HEARS are Triple pressure level (TPL-HEARS), and Low Pressure Condenser (LPC-HEARS). Previous studies revealed the preference of the latter configuration as it allows lower circulation ratios, enhances the refrigeration effect, and could achieve a COP up to 1. Moreover, LPC configuration is suitable with single, double, and variable-effect absorption systems with a COP of above unity. In turn, the TPL-HEARS notably enhances the absorption process, particularly when a variable geometry ejector is utilized. This configuration could obtain a COP around 1.1, but only with high-density refrigerant vapor. Lately, to attain the advantages of both configurations, some studies investigated the viability of adding two ejectors to the cycle. This paper meticulously reviews investigations conducted on the emerging dual ejectors-absorption refrigeration technology. This paper reveals the general performance trend and the maximum attainable COP by each type of hybrid ejector-absorption refrigeration system. DEARS and Ejector-driven absorption refrigeration systems (ED-ARS) could achieve COP that ranges between 1.2 and 1.46. The use of a flash tank and a RHE is essential in NH_3/H_2O HEARS. At high generator temperatures (of 120–170 °C), DEARS was found to be the system with less complexity and best performance. Nevertheless, the performance of the DEARS might drop significantly if the heat source temperature is fluctuating. Thence, the variable-effect HEARS is considered the best alternative. The capability of HEARS to be integrated with different power generation cycles is also highlighted. Finally, the review presents possible future research opportunities to improve the absorption refrigeration technology.

Keywords: absorption refrigeration; cooling system; hybrid refrigeration system; combined ejector absorption system; dual ejectors

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1. Introduction

1.1. Background

Global warming and climate change are leading a global trend for the utilization of low-grade heat and renewable energies. Excluding chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), greenhouse gas (GHG) emissions from refrigeration and air-conditioning sectors are expected to increase from approximately 349 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010 to 1596 million $MtCO_2e$ in 2030 [1].

The need for refrigeration is global. Refrigeration is indispensable for several industries such as food and beverage, in addition to preservation of many medical items such as vaccines and blood. From an environmental stand of view, thermally driven refrigeration systems are considered a reasonable substitution for conventional vapor compression systems. There are meticulous efforts to phase out the use of hydrochlorofluorocarbons (HCFCs). However, the majority of refrigerants that are currently used in DX units are, to a certain degree, harmful to the environment. Either they have a slight ozone depletion potential (ODP) or global warming potential (GWP). However, absorption chillers predominantly use ammonia or water as working refrigerants, and both are classified as environmentally friendly refrigerants with ODP and GWP equal to zero. Thence, thermally driven refrigeration systems have two distinctive features over the DX systems: the use of environmentally friendly refrigerants and the ability to utilize low-grade heat sources to drive the system [2]. Those two features make the thermally driven systems more attractive from an environmental perspective [3].

1.2. Overview of Absorption Refrigeration Systems

The most commonly used thermally driven refrigeration systems are ejector refrigeration system, adsorption refrigeration system, and absorption refrigeration system. The absorption refrigeration system (ARS) is comprised of absorber, generator (desorber), evaporator, condenser, two throttling (expansion) valves, and solution heat exchanger. ARS could produce large refrigeration power in comparison to the other two thermally driven systems. However, it has low COPs, high maintenance costs, and a large size of the system [4]. Therefore, many developments were carried out on the basic cycle to enhance its performance. Predominantly, developments on the ARS' performance targets enhancing heat and mass transfer, absorption, and desorption processes, and/or miniaturize the size of the system. The developments are usually accomplished by employing different working solution, using more effective heat exchangers' alternatives, and/or adding components to the basic cycle. Figure 1 illustrates some of the prevalent developments in absorption refrigeration systems.

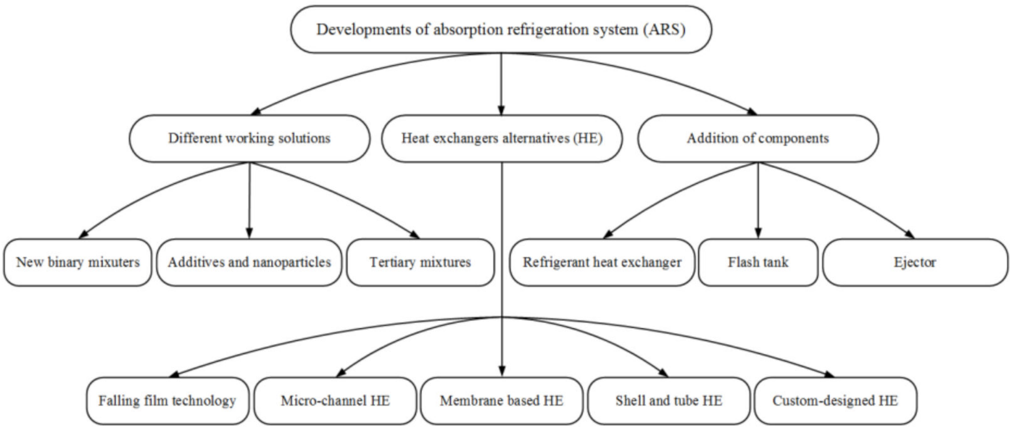


Figure 1. Common ways for developing an absorption refrigeration system.

The first method to improve the absorption refrigeration system is substituting the conventional mixtures (such as NH_3/H_2O and $H_2O/LiBr$) with other working fluids that have better thermodynamic and thermos-physical properties for higher efficiency and better heat and mass transfer processes. Several binary and tertiary mixtures, as well as mixtures with additives and nanoparticles, were proposed. Sun et al. [5] presented a thorough review on working fluids used in absorption cycles, including absorption chillers, heat pumps, and absorption transformers. The authors classified the working fluids into five categories according to prevalent absorbents, while Boman et al. [6] developed a thermodynamics and heat transfer screening method for comparison of working pairs used in absorption heat pumps. The authors applied the method to over 40 potential working fluids and, thence, recommended the best alternatives for cooling and heating modes.

Another area of improving ARS is the type and design of the main components in the ARS. One major drawback that makes the ARS less competitive in the market is the large size of the system. Accordingly, system components should be miniaturized and simultaneously designed in a way that enhances the heat and mass transfer. Narváez-Romo et al. [7]

reviewed the heat and mass transfer correlations for absorption machines that involved falling film technology. The correlations were classified according to typical operating conditions of both refrigeration and air-conditioning applications. The summary permitted the comparison between the two applications when working under the same operating conditions. It also affirmed that the correlations had different behaviors in each application, with some observed divergence between the theoretical and experimental studies. The authors recommended to carry out future research under more realistic operating conditions for the sake of understanding the actual behavior of transfer mechanisms in falling film heat exchangers.

Practically, Meacham and Garimella [8] experimentally investigated an absorber that contained falling film of an Ammonia–Water solution and micro-channels within which vapor flows countercurrent. The experimental setup had an optical access to evaluate the solution distribution mechanism. Even though the surface area of the absorber was only 30% of the surface area of the conventional absorbers, it could transfer approximately similar rates of heat and mass. This improvement was attributed to the enhancement in the flow distribution. The authors claimed that their design could be utilized as any of the main components of the ARS (absorber, generator, condenser, and evaporator). Similarly, Determan and Garimella [9] developed a compact microchannel device that can be utilized as absorber or desorber. The result of the study showed the versatility of their design. The study also concluded that the technology of microchannel heat and mass transfer help to miniaturize the system envelope. On the contrary, González-Gil et al. [10] argued that falling film technology does not aid in the reduction of absorber size, which was also considered as a serious challenge for commercialization of small-capacity absorption refrigeration machines. Hence, the use of a hydrophobic membrane module at the liquid/vapor interface was presented as a competitive alternative to fabricate compact absorbers for absorption refrigeration machines. Yet, the use of this technique has not been examined in air-cooled systems.

The two types of membrane contactors that have drawn the attention of investigators in the field of absorption refrigeration systems were flat sheet membrane contactor and hollow fiber membrane contactor [11]. The pressure drop is usually small in the former type due to the parallel plates' design. Thus, it suits the aqueous solution of H_2O/LiBr. On the other hand, the hollow fiber contactor is usually used in water/ammonia absorption refrigeration systems as it has an external transverse flow that allows more efficient mass transfer. It is essential to select a membrane module with adequate characteristics in order to get the maximum use of mass transfer potential for such modules. Asfand and Bourouis [11] reviewed various membrane contactors suitable for absorption systems. The authors concluded that it is realizable to design compact and improved components through the use of membrane contactors. Such contactors significantly enhance the heat and mass transfer processes due to the high area-to-volume ratio. Since the size of the generator and the absorber are the major cause of the large size, consequently, membrane-based generators and absorbers allow considerable miniaturization of ARS' size.

For the shell-and-tube absorber, Fernández-Seara et al. [12] analyzed the mass and heat transfer processes for water absorbing an ammonia refrigerant in a co-current vertical tubular heat exchanger cooled by water circuit. The model was developed based on heat and mass transfer equations, in addition to mass and energy balances, to comprehensively describe the absorber behavior. Experimentally, the absorption process in the vertical tube usually takes place on various kinds of flow patterns such as bubbly, slug, and churn patterns. The authors applied their model on each pattern separately. Besides the simultaneous mass and heat transfer processes in vapor and liquid phases, the model also considered heat extraction by cooling water. The results obtained by applying the finite difference model revealed that rapid progress in the absorption process took place in the slug and the churn regions. In contrast, in the bubbly region it slowed down. Additionally, the temperatures of the interface and the bulk liquid were almost equal. Thus, the heat transfer barely took place in the vapor phase. Additionally, owing to the heat generated at the beginning of the exothermic absorption process, some water desorption was expected. This phenomenon was also reported for a counter-current flow [13,14] and for co-current bubble absorbers [15].

Regarding H_2O-LiBr absorption systems, Wu et al. [16] designed and tested an alternating structure for an absorber. The absorber comprises mesh screens that were inserted into horizontal tubes gaps. Subsequently, the solution would successively flow through the tube and mesh packing region. The design was experimentally investigated to characterize the heat and mass transfer during the absorption process, then compared with a conventional horizontal tube scheme. The absorption and overall heat transfer coefficients, as well as the average mass transfer rate, increased by 29.4%, 9.89% and 17.2%, respectively. Consequently, a 6.23% increase in the cooling effect was obtained. The improvements were attributed to the enlargement of the absorption area, slowing down of the flow, and well mixing of the solution. According to the findings of this study, it is recommended to investigate the performance of this design with other working fluids such as aqua–ammonia solution. In turn, Olarte-Cortés et al. [17] designed an absorber with a stainless steel shell and tar-impregnated graphite disks arranged in a column internally. The graphite is impregnated with tar to enhance the absorber thermal conductivity and corrosion resistance. The experimental results showed that when the Reynold number increases from 110 to 144 the heat transfer coefficient reached up to 954 $W/m^2{\cdot}K$, which was comparatively high. However, it started to decline when the Reynold number exceeded 147. The thermal loads obtained by this absorber were similar to those obtained by the studies conducted by Medrano et al. [18] as well as Miller and Perez-Blanco [19], but the coefficients of internal heat transfer exceeded those obtained by Yoon et al. [20] and Medrano et al. [18].

Absorption refrigeration systems could also be developed by adding sub-components such as a refrigerant heat exchanger (RHE), flash tank, and ejector. After conducting a thorough review on the use of RHE in an absorption system, Abed et al. [21] concluded that adding RHE had slight influence in increasing the COP of ARS (4–8%). Additionally, to increase the thermal load of the evaporator and, consequently, the COP, the effectiveness of the RHE must be high. Moreover, other studies contained reviews of different improvements in absorption refrigeration systems. Besides the aforementioned enhancement aspects, the authors stated some conclusions: For instance, multi-effect cycles are more promising than single-effect ones [2,22], combined vapor compression–absorption refrigeration systems outperform the conventional ARS [23], and the need for improving the design of the distillation column, rectifying column, and most importantly the stripping section within the generator [21]. The authors also recommended to apply the above modifications on domestic refrigerators and air conditioners, increase the stripping stages of the desorber, and using working solutions that prevent corrosion and utilize nanoparticles. In turn, incorporating a flash tank in the ARS increases the COP of the system by means of increasing the quality of refrigerant exiting from the evaporator [24]. Moreover, one of the effective utilization and improvement approaches of the ejector is to integrate it with absorption refrigeration systems [25]. Research trials carried out on improving the performance of absorption system by utilizing an ejector will be elaborated on in the following sections. Several scholars claimed that it is realizable and economically viable to drive the various configurations of ARS by means of solar thermal systems [26,27] and photovoltaics [28]. Although the claim was proven via several experimental investigations [29], the efficient and economic system operation was limited to specific working solutions, most probably NH_3-H_2O [30] and water-based solutions [31]. Moreover, in solar-driven ARS, H. Sheikhani et al. [32] insisted on the importance of using auxiliary devices such as backup heating units and storage tanks.

To recapitulate, ARS still requires further improvements to be economically attractive. Various development aspects on ARS are promising and realizable, particularly aspects related to utilization of ejectors and the design of the ARS’ components. Utilizing ejectors in ARS enhances evaporation, condensation, and absorption processes, while innovative design of absorbers, desorber, and heat exchangers will considerably miniaturize the size of the system and boost the heat and mass transfer. Therefore, the combination of adding ejectors and the use of effective system components is vital, as they could increase the COP and reduce the cost. In the literature, there is a lack of research on the ejector performance with the different types of absorber designs. This issue is extended to the use of dual ejectors in ARS.

Regarding review studies done on ejectors and their use in cooling and refrigeration systems, Tashtoush et al. [33] carried out a thorough review on ejector design, performance, and applications, whereas Aidoun et al. [34] reviewed the present developments in experimentation, modeling, and applications of ejectors for refrigeration and heat pumps. Milazzo and Mazzelli summarized the potential prospective on ejector refrigeration in the future [35], while Besagni et al. [36] presented a comprehensive review on ejector refrigeration technologies and evaluated the working fluid that suits such technologies, but the hybrid ejector-absorption technology was merely discussed briefly.

This current review study emphasizes hybrid ejector-absorption refrigeration technology. Firstly, the concept of a hybrid ejector-absorption refrigeration system and associated working solutions are presented. Then, the recent developments on such systems are discussed in detail, with more emphasis on dual ejector-absorption refrigeration systems. In addition, the integration of hybrid ejector-absorption systems with other systems is briefly discussed. Finally, the prospective enhancement aspects of hybrid ejector-absorption refrigeration systems are demonstrated.

2. Ejectors and Hybrid Ejector-Absorption Refrigeration System (HEARS)

The principle of ejector was introduced in 19th century and used on steam locomotives [37]. Ejectors are devices that use a high-pressure fluid stream to entrain a low-pressure fluid and discharge the resultant mixture of the entrainment process with intermediate pressure. Ejectors' principle of operation is always the same: A high-pressure stream (the primary fluid) transfers a portion of its energy to a low-pressure stream (the secondary fluid), then discharges the mixture of the two streams with a "back pressure" that would be between the pressure of the primary fluid and the pressure of the secondary fluid. The ratio between the back pressure and the secondary fluid pressure is referred to as compression ratio (or pressure lift), whereas the ratio between the mass flow rates of the primary fluid and the secondary fluid is called the entrainment ratio. Mainly, there are three operational variables that govern the ejector performance (the entrainment ratio), namely, the primary fluid pressure, the secondary fluid pressure, and the back pressure [38]. Tashtoush et al. carried out a thorough review of ejector design, performance, and applications. The authors investigated the ejector geometrical and operational parameters and their effect on the ejector performance. The ejector critical parameters were area ratio, compression ratio, and expansion ratio [33].

The function produced by ejectors could be utilized in an absorption refrigeration cycle in several ways. The high-pressure energy in the vapor produced in the desorber could be utilized to entrain the vapor exiting from the evaporator. Consequently, the amount of the refrigerant that flows into the condenser and the evaporator increases; thus, the refrigeration power increases. Correspondingly, according to other studies, adding an ejector before the absorber enhances the absorption process [39]. These improvements are applicable to various cycle configurations such as single effect, variable effect, and double-effect absorption cycles. Moreover, some studies demonstrated the feasibility of utilizing variable geometry ejector in achieving optimum system performance [40,41]. Figure 2 shows different categories of hybrid ejector-absorption refrigeration systems that have been investigated in the literature.

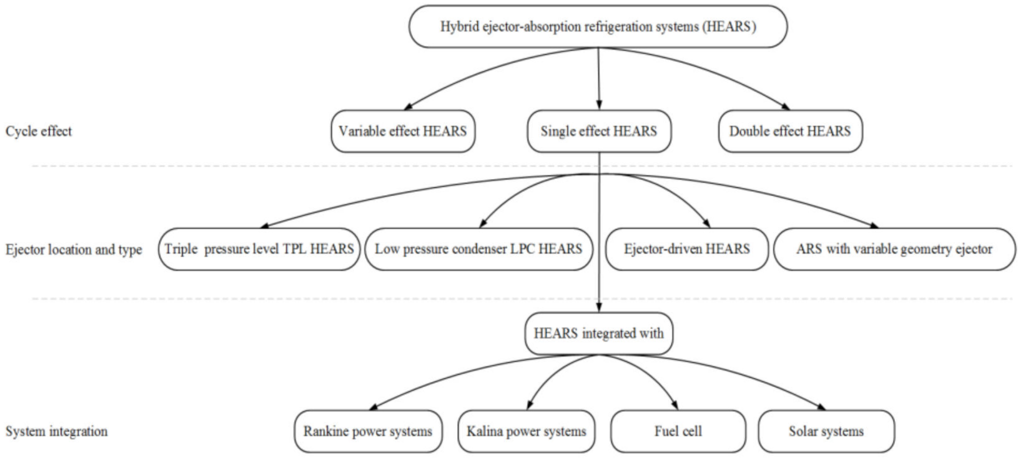


Figure 2. Different types of hybrid ejector-absorption refrigeration systems.

One of the earliest studies about incorporating ejectors into absorption refrigeration systems was done by Kuhlenschmidt in 1973 [42]. The author patented a cycle configuration similar to that of double-effect absorption system. The cycle involved an ejector incorporated between the evaporator and the absorber with a secondary flow from a second generator. In the case of single-effect systems, the triple pressure level (TPL) configuration (Figure 3) uses a liquid–gas ejector to entrain refrigerant vapor from the evaporator, and it preserves the absorber at higher pressure than that of the evaporator without any additional energy consumption. Thus, the hybrid ejector-absorption cycle operates at three pressure levels [39,43]. Moreover, due to the generation of liquid spray, in addition to the considerable sub-cooling of the weak (in-refrigerant) solution in the heat exchanger, the mixing "or absorption" process in the ejector is intensified [39]. However, such systems are only operable under high-density refrigerant vapor because liquid-driven ejectors are not suitable for low-density vapor (for example, water vapor, which is used in $H_2O/LiBr$ absorption refrigeration systems) [21].

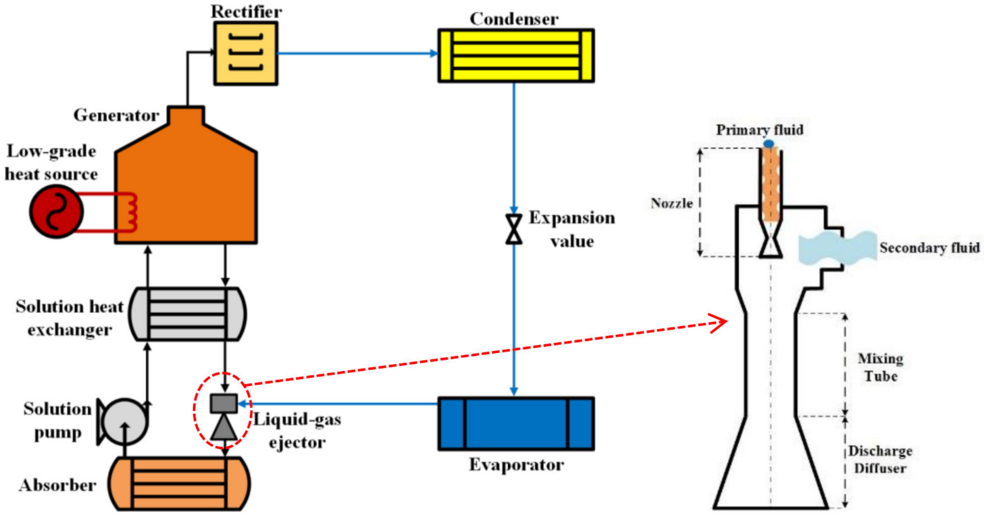


Figure 3. Schematic diagram of Hybrid Ejector-Absorption Refrigeration System (HEARS), Triple pressure level "TPL" configuration.

On the other hand, Aphornratana and Eames [38] proposed an integration approach by placing the ejector between the generator and the condenser. $H_2O/LiBr$ solution was used as a working fluid. The primary fluid was high-pressure water vapor from the generator. In this case, if the condenser pressure (the back pressure of the ejector) is kept at a specific designated narrow range, there will be fixed values of COP and entrainment ratio for each given value of the evaporator and generator pressures. On the other hand, if the back pressure exceeds a particular value (the critical back pressure), the COP and entrainment ratio will encounter a dramatic drop. Further increase in the back pressure might result in a zero entrainment ratio and could reverse the flow in a situation that eventually leads to ceasing the ejector operation. This configuration is known as low-pressure condenser (LPC) configuration (Figure 4). Absorption refrigeration cycle operates in LPC configuration, which requires higher generator temperatures, which implies lower exergy efficiencies. However, because of its compression ratio, it can operate with a circulation ratio that is four times less than the conventional absorption refrigeration cycle. The high driving temperatures required for this cycle can be supplied effectively by sustainable energy sources such as solar systems [44]. Shahboun and Adeilla [45] carried out thermodynamic analysis on a proposed solar ejector-absorption refrigeration system. The authors claimed that the modified system surpasses the conventional system by 50–71% within the range of condenser temperature of 20–40 °C. Moreover, Sioud et al. [46] showed that a linear Fresnel solar concentrator could drive a 60-kW HEARS working under generator operating conditions in the ranges of 198 kPa–270 kPa and 180 °C–210 °C. The entrainment ratio increased with the evaporator temperature, but it was inversely proportional to the condenser temperature [43]. In general, it increased with the area and the expansion ratios and decreased as the compression ratio increased [47]. In order to maintain the driven fluid (from evaporator) at maximum entrained values it is essential to have variable area ratio; this was considered a pivotal factor in avoiding the sudden drop in the contribution of the ejector refrigeration sub-cycle.

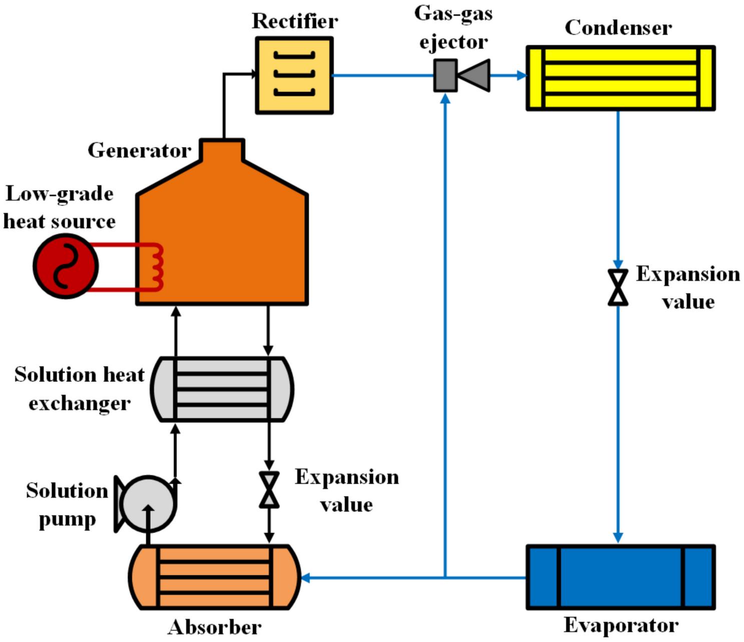
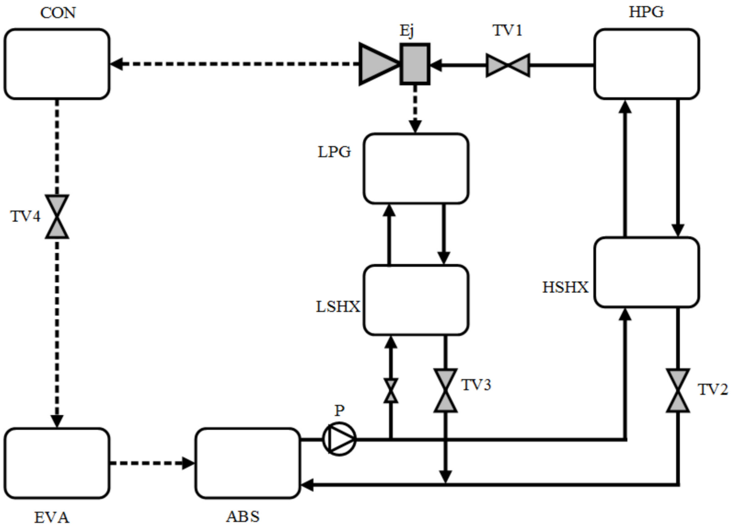


Figure 4. Schematic diagram of Hybrid Ejector-Absorption Refrigeration System (HEARS), Low-pressure condenser "LPC" configuration.

The use of an ejector enables the absorption cycle to operate at lower circulation ratios [48]. Subsequently, the refrigeration effect could be increased by operating the evaporator at lower temperature [48], and, hence, the COP increases [40]. Moreover, low circulation ratios allow the utilization of an air-cooled absorber. The advantage is to eliminate the need for the cooling tower required for a water-cooled absorber; thus, the total cost is reduced. On the contrary, using air-cooled absorbers occupies larger spaces in the ARS. Furthermore, due to heat transfer characteristics of the coolant, air-cooled absorbers usually operate at higher concentrations and temperatures, thus increasing the chance of crystallization. A further advantage arises when the generator operates at a higher pressure than the condenser as a consequence of using an ejector. This pressure difference between the two components permits the increase of the solution temperature without the risk of crystallization. The precipitation of solution crystals occurs when the concentration is high and/or the temperature is relatively low. The two conditions are most likely anticipated at the exit of the heat exchanger. The phenomenon of solution crystallization has a crucial impact on the system performance and failure. The main reasons for crystallization are high surrounding temperature, air leakage into the cycle, high heat input, failure in the dilution process after shutdown, and low chilled water supply [49]. Various techniques are proposed to avoid crystallization. For instance, the use of a ternary mixture like $LiBr+ZnBr_2/H_2O$ improves the solution solubility [2]. Moreover, Liao and Radermacher [49] believe that increasing the chilled water temperature and/or reducing the exhaust temperature are effective control strategies to prevent crystallization in integrated cooling–heating power systems.

The hybrid ejector-absorption refrigeration systems (HEARS) are still not common due to their relatively low COPs and the severe performance degradation that occurs when the ejector operates out of the design conditions [50]. The design of an appropriate ejector is a challenge in designing a hybrid system [51]. Numerous experimental investigations and mathematical modelings using Engineering Equation Solver (EES) were conducted on HEARS, seeking techno-economical enhancement of the system performance, such as increasing the COP, decreasing the required concentration of the working solution, decreasing the capital cost, and increasing system reliability. On the other hand, various studies assessed the system performance with the change of ejector location in the absorption cycle and deduced that exergy destruction in the steam ejector is significantly higher than in the solution–refrigerant ejector [44,52].

The use of an ejector in double-effect ARS has demonstrated its feasibility at specific operating conditions. According to the computational model developed by Farshi et al. [53], low-grade temperature sources could effectively be used to drive such cycles. Nevertheless, the cycle with an ejector outperformed the conventional double-effect absorption cycle at a narrow range of operating conditions. Additionally, the exergetic efficiency of single- and double-effect absorption cycles increased with the driving temperature in the generator to a peak value, then started to decrease. In contrast, this did not occur when the ejector was added to the double-effect absorption cycle, and it almost remained constant. This could be attributed to the relatively moderate range of driving temperatures at which the hybrid cycle operated. Another advantage of the hybrid cycle over the conventional double-effect cycle was related to possibility of crystallization. Under the studied operating conditions, the solution at the absorber entrance was less susceptible to crystallization in the hybrid cycle with respect to the conventional cycle. Furthermore, under similar operating conditions, the hybrid cycle was found to be more economical [54]. Shi et al. [55] proposed the use of a multi-heat source to drive a HEARS at different temperature levels. The ejector used the water vapor exiting from the high-pressure generator to entrain the vapor generated in the low-pressure generator. In this cycle (Figure 5), more water vapor could be extracted from the low pressure generator than in the conventional double-effect cycle. In addition, the temperature level of the heat source required to drive the low pressure generator could be as low as 85 °C, which is feasible to be provided by solar collectors. Moreover, the heat source temperature level in the higher pressure generator (185–215 °C) was considerably lower than that required in commercially available double-effect systems [55]. This system could achieve up to a COP of 0.95 under a hot air inlet temperature of 215 °C.



HPG: high pressure generator, **LPG**: low pressure generator, **HSHX**: high-solution heat exchanger, **LSHX**: low-solution heat exchanger, **ABS**: absorber, **EVA**: evaporator, **CON**: condenser, **Ej**: Ejector, **P**: pump, **TV**: throttling valve

Figure 5. HEARS driven by multi-heat source [55].

To deal with the unsteady operating conditions that are usually associated with absorption refrigeration systems, Yan et al. [56] suggested the use of an ejector with variable-effect ARS. The system was fabricated according to the configuration proposed by Hong et al. [57] in which the cycle works interchangeably between single- and double-effect configuration according to the temperature level of the heat source. Yan et al. did not need to add extra heat source as it was done by Shi et al. [55]. Additionally, the ejector was the key component that influenced the variation of the cycle effect. The results indicated that the performance of the developed variable-effect prototype outperformed the performance of the conventional single-effect cycle, and it had much lower generator temperature than the conventional double-effect cycle (about 20 °C less). The experimental results were verified with the theoretical results reported in [58,59] and under similar conditions, except that evaporator temperature was lower by 5 °C. The validated results of this system substantiated that the cycle had a highly reliable performance under a wide range of operating conditions. To improve the performance of this configuration, Hong et al. [57] recommended to replace the ejector by an expander-compressor because this latter has higher efficiency.

Recently, Sioud and Bellagi [60] developed a mathematical model of a hybrid system in which an external steam ejector loop was used to activate an H_2O/LiBr single-effect absorption refrigeration system. Numerical results revealed that the entrainment ratio of the ejector was directly proportional to the steam pressure and condenser temperature, while it was inversely proportional to the generator temperature and a negligible effect was recorded for the evaporator temperature. Additionally, at $T_e = 4$ °C, $T_c = 37$ °C, and within a narrow certain range of activation temperature (75 °C $< T_g <$ 85 °C) the system achieved high values of COP that were comparable to that of a conventional double-effect configuration. Nevertheless, outside this range the proposed system behaved almost similarly to the conventional single-effect absorption cycle. The authors also investigated a double-effect configuration in which the ejector was used to recompress part of the vapor exiting from the high pressure generator to reheat the solution. Regarding ejector design and performance in such a cycle where the ejector is used in external loop to drive the cycle, the major conclusion of this theoretical study was the relation "ratio" between the high pressure generator and the primary steam pressure that should be kept as low as possible in order to achieve the maximum performance with a driving temperature that is about 20–25 °C less than in the conventional double-effect cycles [61].

2.1. Utilizing Adjustable Ejector in Hybrid Ejector-Absorption Refrigeration Systems

Incorporating an ejector into an absorption cycle driven by a low-grade heat source such as solar energy offers a simple and low-cost solution for the operation within a range of set temperatures [62]. Nevertheless, the ejector's operation mechanism is complicated due to the interactions occur during the mixing of two streams in supersonic and subsonic flow conditions [63]. Under variable operating conditions, the geometrical design of the ejector should be carefully carried out to maximize the COP [51] or variable geometry ejectors could be utilized, as they were theoretically investigated by Vereda et al. [40] where the solution expansion valve was replaced with an ejector whose dimensions were fixed except the nozzle area, which was adjustable. The authors aimed to investigate the effect of ejector geometry on the system performance and to set the optimal range of heat source temperature within which the use of a practical ejector becomes beneficial. The developed simulation used a NH_3-$LINO_3$ solution, which was based on novel models for detached heat transfer regions in plate heat exchangers. The results were exhibited as a function of external temperatures and the cycle performance was recorded for various ejector mixing tubes with fixed diameters. The results demonstrated that the use of an ejector allows operating with a generator activation temperature of 9 °C less in comparison to the conventional cycle and achieved higher COPs at temperate source temperatures. This adjustable ejector develops three functions: expansion control valve of variable geometry, booster of the absorption process using no external energy, and jet bubble ejector [48]. It was observed that the ejector mixing tube had a significant effect on the COP (Figure 6). However, at a fixed diameter of the mixing tube, the max COP of the cycle was less than the COP of the conventional cycle, particularly at smaller diameters. In smaller diameters, there is much reduction in the activation temperature, yet the peak value of the COP was less than that of the conventional cycle. Despite this, and relying on the ejector geometry, the ejector-absorption cycle exhibited a higher COP when the heat source inlet temperature ranged between 81–92 °C. Otherwise, under the considered hypothesis and high source inlet temperature, modifying the ejector-absorption cycle to a conventional cycle, via bypassing the ejector, was more suitable.

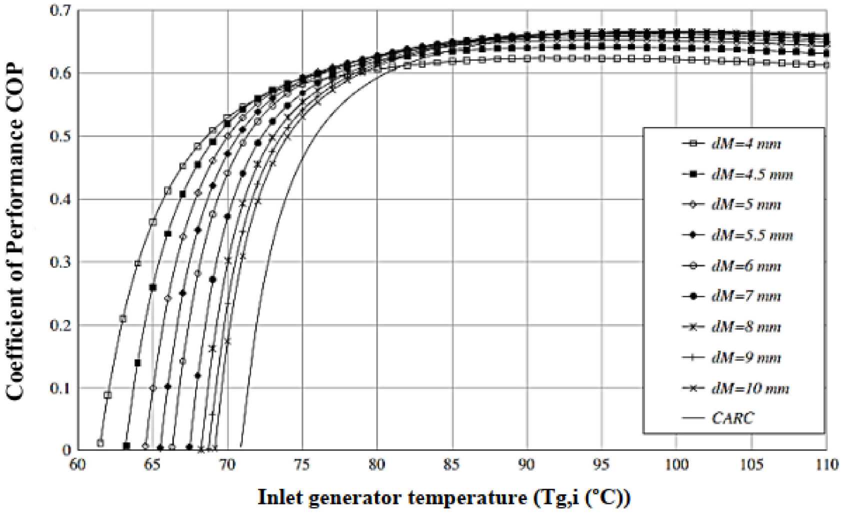


Figure 6. Variation of COP with inlet driving temperature for different mixing tube diameters (dM) of the ejector [40].

2.2. Hybrid Ejector-Absorption Refrigeration Systems with Flash Tank

Adding a flash tank will improve the performance of the HEARS [64]. The use of the flash tank optimizes the entrainment ratio of the ejector, reduces the flash gas delivered to the evaporator and, hence, increases the cooling effect. The vapor refrigerant would also aggravate the pressure drop within the evaporator due to the increase in void fraction [24]. Reported experimental testing [65], mathematical modeling using Fortran Language [66], and numerical simulation using Aspen-Hysys [67] demonstrated the benefits of adding a flash tank in optimizing the ejector performance and the evaporator thermal load.

When a flash tank is added to HEARS, attention should be paid to the design of ejector geometry and critical operating temperature. For low evaporator temperature (−15 °C–0 °C), the hybrid system with a flash tank yields a higher COP than a hybrid system without flash tank. However, for air-conditioning purposes where evaporator temperature is usually above 3 °C, the hybrid systems without a flash tank experience better COPs, as shown in Figure 7 [24]. This difference in performance is attributed to the influence of the flash tank on the critical operating conditions of the ejector. Nevertheless, this behavior still requires further investigation.

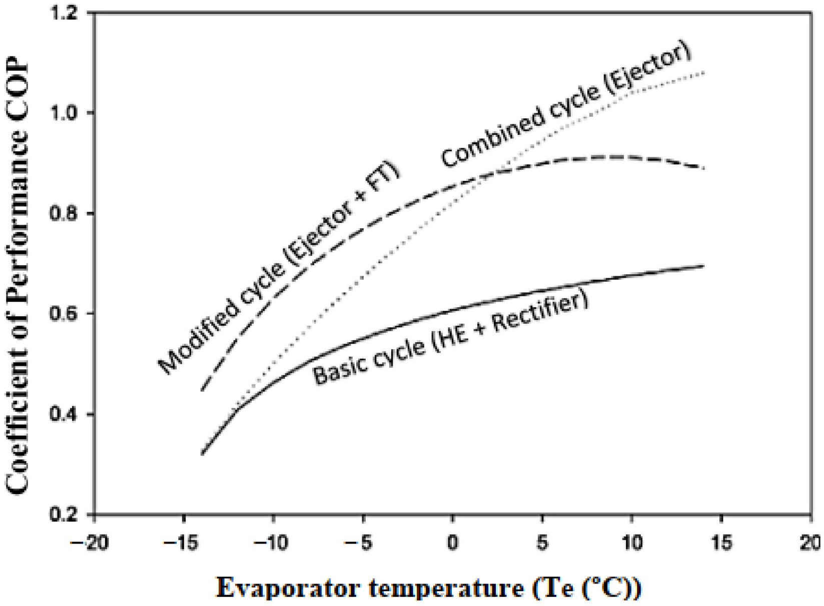


Figure 7. Effect of evaporator temperature on the COP for different cycle configurations [24].

The flash tank pressure is a function of the condenser and evaporator pressures. It is sometimes adjusted to a value that ensures a certain amount of the vapor in the flash tank is entrained in the ejector [24]. The increase in the flash tank pressure increases the entrainment ratio due to the increase in the secondary fluid pressure [43]. This feature moderates the COP drop due to the increase in condenser pressure. This explains the reason that HEARS with a flash tank performs better than HEARS without a flash tank when the condenser pressure increases.

Relying on the second law of thermodynamics, Sirwan et al. [68] evaluated an ejector-absorption cycle after adding a flash tank between the evaporator and the condenser. Under operating conditions of T_g = 85 °C, T_c = T_a = 30 °C, and T_e = 0 °C, the developed model evaluated the exergy losses and the entropy generation of each component. The flash tank prevents the refrigerant vapor, which has lower heat transfer coefficient than the liquid phase, from getting into the evaporator and reduces its cooling effect. Consequently, the COP and the exergetic COP increased from 0.844 to 0.875 and from 0.459 to 0.476, respectively. This improvement in the performance of a hybrid cycle was substantiated by the statistical *t*-test [24,68]. Thereafter, a refrigerant heat exchanger, "RHE", was introduced (Figure 8) and the solution pathlines were modified by Abed et al. [69]. The enhancement of this modification resulted in an increment in the COP by 4.2% and 8% due to the addition of the RHE and the rearrangement, respectively. The ejector efficiency would improve if the booster (or flash gas valve) was removed from the refrigerant pathline and allowed the pressure of the secondary fluid to be the same intermediate pressure of the flash tank [64].

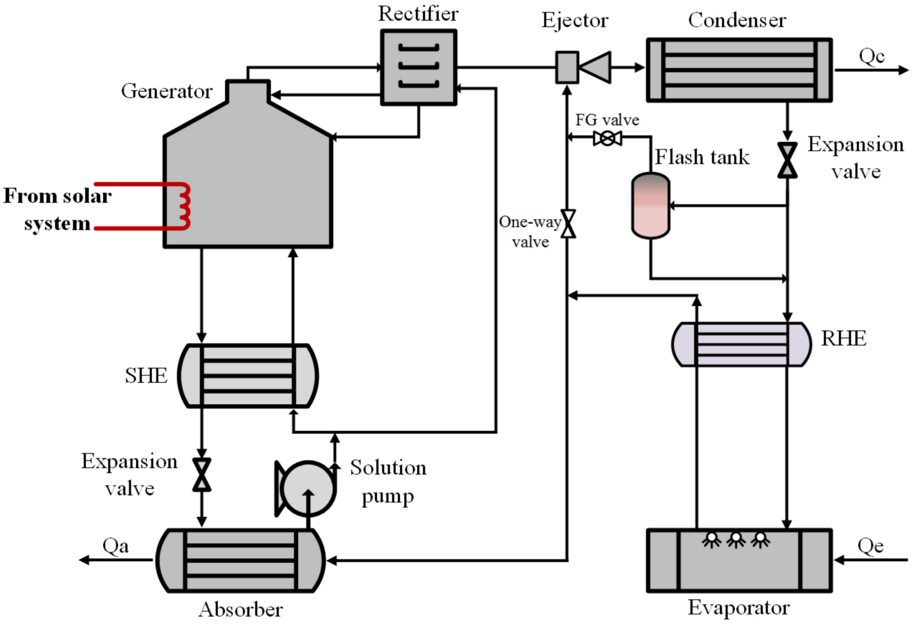


Figure 8. Schematic of HEARS with flash tank and RHE [69].

Similarly, Ben Zid et al. [67] conducted a simulation for an absorption refrigeration cycle comprised of an ejector interposed between the generator and the condenser. In addition, a flash tank between the condenser and the evaporator was also utilized. Compared to a conventional single-effect cycle, the simulation concluded that an improvement in the COP from 0.64 to 0.76 was recorded. Moreover, one of the configurations that was investigated by Abed et al. [51] included adding a flash tank to a single ejector absorption refrigeration system. This configuration was experimentally approved to perform better (in terms of generator and evaporator thermal loads) than the single ejector configuration under almost similar climatic conditions. Moreover, adding a second ejector to the cycle with a flash tank would further decrease the generator thermal load, increase the evaporator thermal load, and, hence, improve the COP of the cycle [51].

In the LPC configuration, the system performance can be improved by adding a splitter downstream of the ejector before the condenser [44]. The splitter divides the discharged refrigerant vapor from the ejector into two parts that are sent to the condenser and the absorber. This latter can operate at a pressure equal to that of the condenser (three times greater than evaporator pressure). In this case, the absorber operates at a pressure higher than in single and dual ejector absorption refrigeration systems with separation tanks [44].

2.3. Working Solutions in Hybrid Ejector-Absorption Refrigeration Systems

Most of the working fluid pairs used in ARS can be used in HEARS. However, some limitations might emerge due to the characteristics of the flow in the ejector. The simplicity and low cost of the ejector make it an attractive option to improve ammonia-based single-effect absorption systems [48]. Aqua–ammonia solution is more stable over wide ranges of temperature and pressure, and it has greater latent heat of vaporization with respect to other commonly used working fluids [2]. The modelling of this hybrid refrigeration cycle showed that using NH_3/H_2O solution increased the COP above unity. However, the exergetic COP was low because the heat source temperature was relatively high [70]. Nowadays,

H_2O/LiBr absorption chiller is the most developed and commercialized product [71]. Ultimately, among various common working solutions and different cycle configurations, the H_2O-LiCl cycle with an ejector placed between the condenser and evaporator was the most feasible cycle in terms of exergy efficiency and COP [44]. This cycle can conveniently be powered by a low-grade heat source such as solar thermal energy or waste heat.

The steam ejectors in the LPC-ARS increase the evaporator pressure up to 3.46 times greater than the evaporator pressure in LiCl- and LiBr-based solutions. In turn, the pressure boost in solution and liquid refrigeration ejectors barely reach 1.016 and 1.050, respectively [44]. Additionally, to achieve higher exergy efficiency in TPL-HEARS, S. Yosaf and H. Ozcan [44] argued that it is preferable to use H_2O/LiCl or H_2O/LiBr. However, this conclusion contradicts the claim of Abed et al. [21] that TPL-HEARS is only functional under high-density refrigerant vapor, and liquid-driven ejectors are impractical for low-density vapor like water vapor. This hypothesis requires further study, and experimental investigation is recommended. Nguyen et al. [72] presented a mathematical assessment for refrigerants suitable for use with ejectors. The selected refrigerants were R1234ze(e), R1234yf, R600a, and R290. The assessment revealed that R290 followed by R1234ze(e) have the best performance among the evaluated refrigerants. However, R290 has a relatively high potential for global warming.

3. Dual Ejector-Absorption Refrigeration Systems (DEARS)

In the absorption refrigeration cycle, condensation, evaporation, and absorption processes could be improved by utilizing an ejector in various locations in the cycle, which eventually leads to higher COPs [25]. This section pertains to the incorporation of two ejectors in the absorption refrigeration cycle and their effect on the cycle performance.

There are some constraints encountered in using booster or FG valve in HEARS with flash tank [24,64,68,69]. One constraint is when a high-energy secondary fluid pushes the flow inside the ejector towards the constant area section, and, hence, leads to an increase in the ejector back pressure (condenser downstream pressure). The entrainment increases when the secondary fluid pressure increases or the back pressure decreases. However, any increase over the optimal pressure value would negatively affect the ejector operating efficiency. Thus, in order to maintain the secondary fluid flow at a fixed pressure in a hybrid ejector-absorption refrigeration system with a flash tank, another ejector can be added between the generator and the condenser to avoid using a booster or FG valve. Accordingly, one ejector works under evaporator pressure and the other ejector works at the intermediate pressure of the flash tank. Moreover, to reduce the water content in the refrigerant, a fraction of the solution pumped from the absorber, in addition to other fractions of vapor from the condenser, is utilized to cool the refrigerant vapor in the rectifier (Figure 9). A mathematical model for this design was developed by Abed et al. [73]. The results revealed a considerable improvement in the COPs (about 11–14% higher for generation temperature between 80 °C and 95 °C) over the single ejector cycle with flash tank.

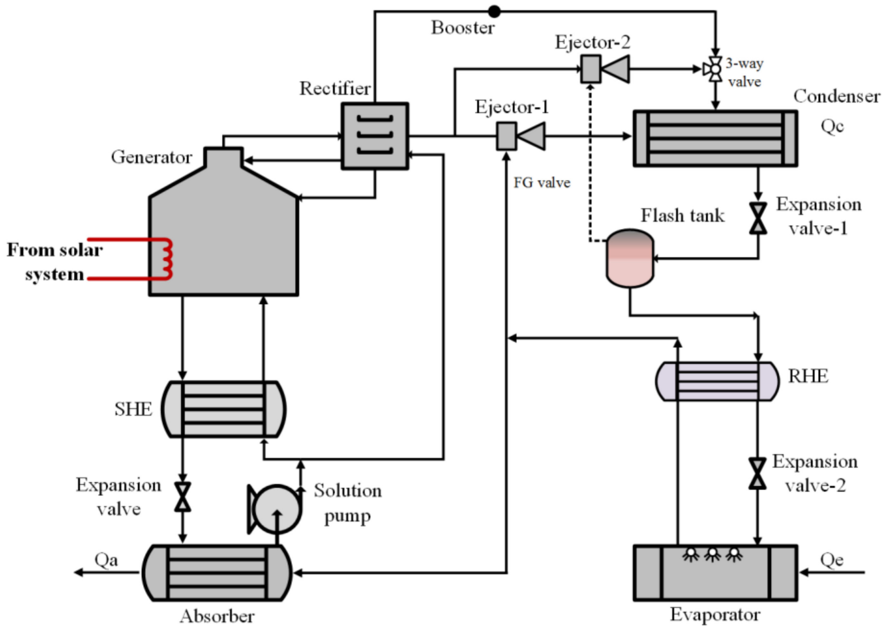


Figure 9. Schematic of DEARS with flash tank and RHE [73].

Thereafter, Abed et al. [51] experimentally investigated the performance of three different configurations of single-effect absorption refrigeration system driven by 40 evacuated tube solar collectors. The first configuration was the absorption refrigeration system with one ejector. The second configuration was with an added flash tank, and the last configuration contained two ejectors. In the last configuration, the use of a second ejector assisted the flash tank in improving the refrigerant quality that flows to the evaporator. Consequently, this allowed the system to operate under greater condenser temperatures [74]. Among the three tested configurations, the dual-ejector system had the best performance as it achieved the lowest thermal loads in the generator, as well as the highest cooling effects (Figures 10 and 11). In turn, the authors identified some challenges during the experimental work. For instance, the system required a prolonged startup period before reaching steady-state operation. Additionally, the authors experienced low system efficiencies at the startup and unsteady operation periods. In addition, the frequent ON/OFF operation reduced the COP compared to the system performance working in continuous steady operation. Furthermore, the refrigerant regeneration process mainly depends on the generator temperature; consequently, care should be taken in the design of the distillation column to ensure proper operation of the absorption cycle under low heat sources.

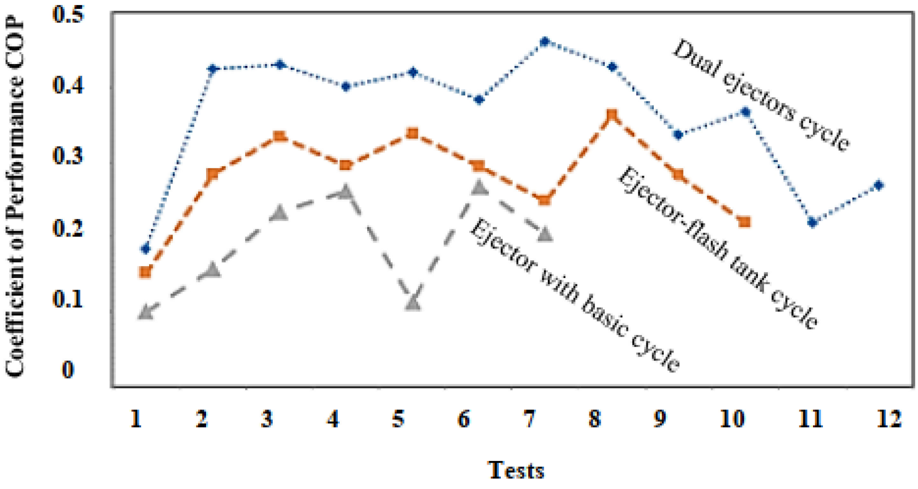


Figure 10. The thermal COP of different cycle configurations in several testing days [51].

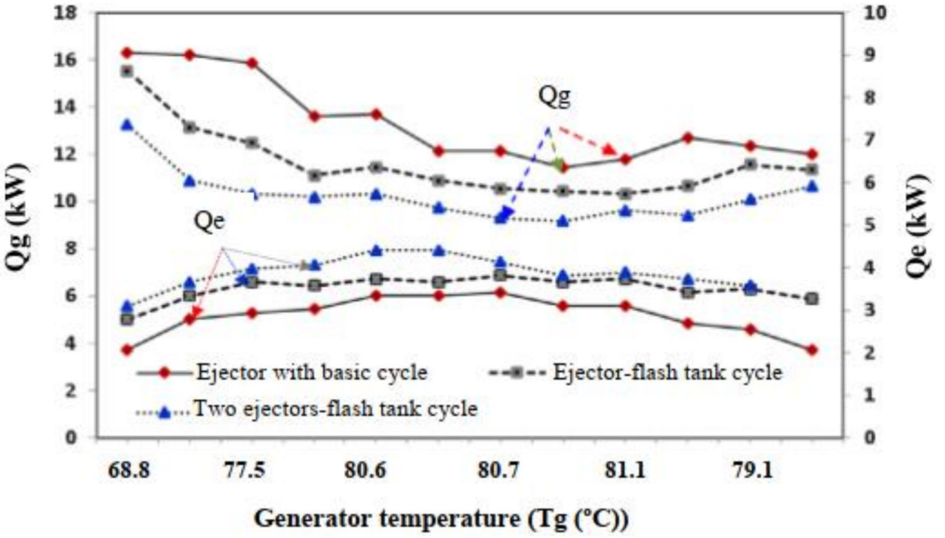


Figure 11. Change of evaporator and generator thermal loads with generator temperature for different cycle configurations [51].

Moreover, Liang et al. [75] carried out a theoretical study on a novel air-cooled DEARS using $NH_3/LiNO_3$ and $NH_3/NaSCN$ as working solutions. The steam-driven jet pump was located upstream of the back flow of the solution heat exchanger (to replace the solution pump in conventional systems), whereas the liquid–vapor ejector was set at the inlet of the absorber (Figure 12).

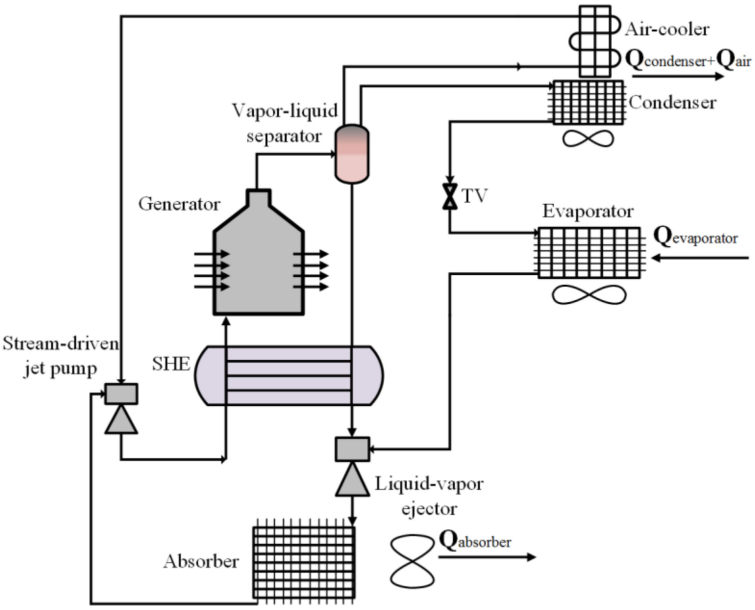


Figure 12. Schematic of ejector-driven DEARS [75].

The performance of the proposed system was compared with the conventional air-cooled ARS. A reduction in the COP of the DEARS was observed and attributed to scarifying part of the refrigerant in the steam-driven jet pump. Nevertheless, a COP of 0.6354 was obtained, which was considered good under low-grade temperature sources like exhaust heat. However, the COP is considered as the ratio between the thermal loads of the evaporator and generator. The work consumed by the fans of the heat exchangers was neglected. However, for absorption systems that utilize air-cooled heat exchangers, it is important to take into consideration the energy consumed by the fans when evaluating the overall system performance. The authors believe that solution temperature at the outlet of the absorber and the pressure ratio of the liquid–vapor are two factors that could enhance the system performance, in addition to the consumption ratio that greatly affects the performance.

Conducting an investigation on the performance of water-cooled DEARS becomes substantial as it resolves the issue of high solution temperature at the outlet of the absorber. Hence, it could achieve a better performance than the corresponding conventional systems. Nevertheless, utilization of an air-cooled absorber and two ejectors assists in designing miniaturized and simplified systems, and broadens the range of appropriate operating conditions, too.

Correspondingly, Yosef and Ozcan [44] used two indirectly coupled ejectors in one of the proposed designs while investigating the effect of ejector location in the absorption cycle. The solution ejector was inserted at the absorber inlet, whereas the liquid–vapor refrigerant ejector was located at the evaporator inlet (Figure 13). Compared to the triple-pressure levels' cycle, this DEARS achieved better performance, particularly at increased absorber pressures. However, this DEARS only utilized NH_3-H_2O as a working fluid because the other working fluids such as H_2O-LiBr and H_2O-LiCl operate at a generator pressure at the range of 3 to 10 kPa. Hence, the pressure recovery in the solution ejector will be comparatively small.

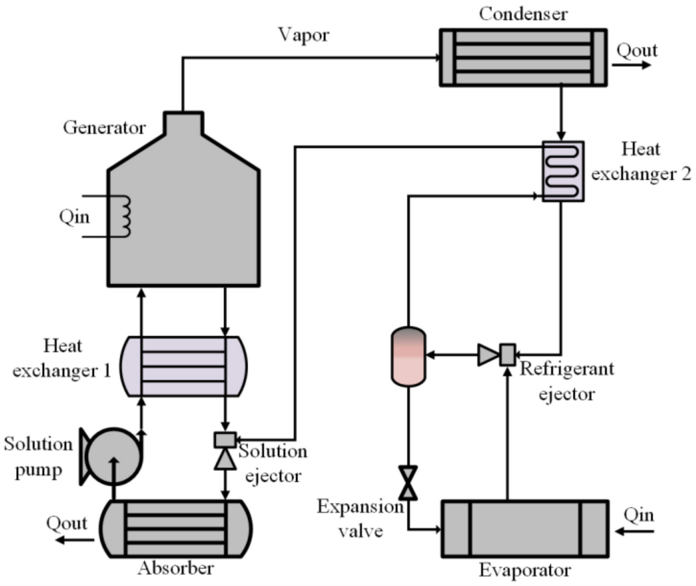


Figure 13. Schematic of DEARS with a separation tank [44].

Following the experimental setup of Abed et al. [51], Al-Shamani [74] proposed the use of the three ejectors (Figure 11) to enhance the system performance. A theoretical study was carried out in which the performance of the NH_3-H_2O absorption refrigeration cycle was investigated for the case of single, double, and triple ejectors. In order to compare the system performances in each case, the simulation was executed under $T_c = T_a = 20$–$50\ °C$, $T_g = 65$–$100\ °C$, and $T_e = -10$ to $15\ °C$ to estimate the thermal loads of the main components. The results indicated that the cycle with triple ejectors realized the lowest thermal loads in the evaporator and the generator, whereas the dual-ejector configuration resulted in the highest generator thermal load, with the evaporator thermal load always less than the basic and single-ejector cycles and slightly higher than triple-ejector cycle. Since the use of ejectors enables the exploitation of the high pressure in the flash tank and the low pressure in the evaporator, in addition to the effective utilization of low-grade heat sources with an unpretentious absorption system structure, a trade-off was made between the multi-ejector absorption cycles to determine the best configuration under various operating conditions. Consistently, the dual ejector absorption cycle achieved the greatest COP (Figure 14). This was attributed to fact that the second ejector tolerates higher condenser temperature as it develops the refrigerant quality at the evaporator inlet, whereas the booster in the triple-ejector cycle pushes the flow toward the constant section of the third ejector and, hence, decreases the flow and entrainment ratio of the third ejector [74].

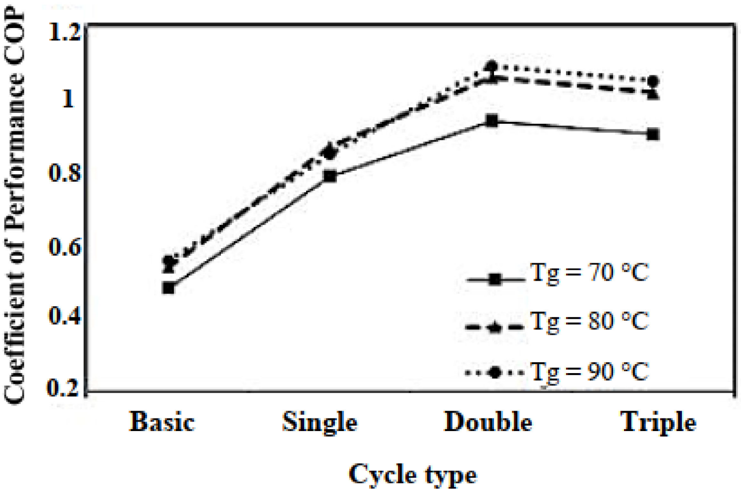


Figure 14. COP for different system designs at different generator temperatures [74].

Khalili and Farshi [76] presented an ARS that involved liquid and vapor ejectors besides RHS. A small compressor was used to compress the amount of vapor exiting from the evaporator and supplied to the vapor ejector as a secondary flow (Figure 15). The simulation results showed that the DEARS exhibited the best performance (highest COP and second law efficiency) in comparison with CARS and TRL-HEARS with activation energy 36 to 55 °C lower than TPL cycle and refrigeration temperature down to −24 °C. In spite of the low evaporator temperatures that indicate great refrigeration capability, attention should be paid to the performance of the vapor ejector as it slightly deteriorates at such low temperatures. The study also pointed out the essentiality of designing the mixing chamber in the liquid ejector with a suitable diameter as it significantly affects the pressure recovery.

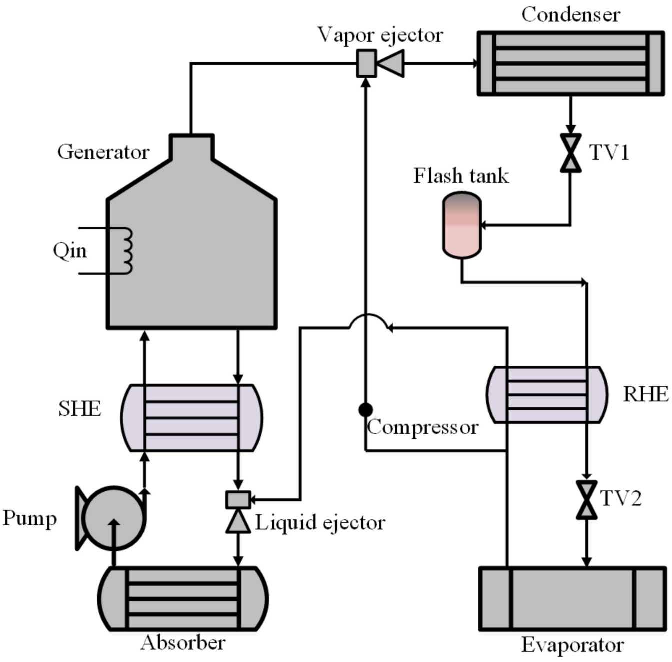


Figure 15. DEARS with SHE, RHE, and small compressor [76].

Thus, the incorporation of dual ejectors into the absorption system was proposed in different locations to form different configurations of DEARS. Five different configurations were identified from the literature. The performance of each DEARS was compared to its corresponding CARS and/or HEARS and/or TEARS (Figure 16). In all investigated configurations, the DEARS always revealed a higher performance with respect to the other corresponding systems. as shown in Figure 16a. The percentages of the COP improvement due to the use of dual ejectors over the other types of absorption refrigeration systems are presented in Figure 16b. The highest COP of a DEARS was achieved by the multi-pressure levels' configuration proposed by Khalili and Farshi [76]. This configuration could achieve a COP of 1.43 compared to the 1.07 that was obtained by the TPL configuration.

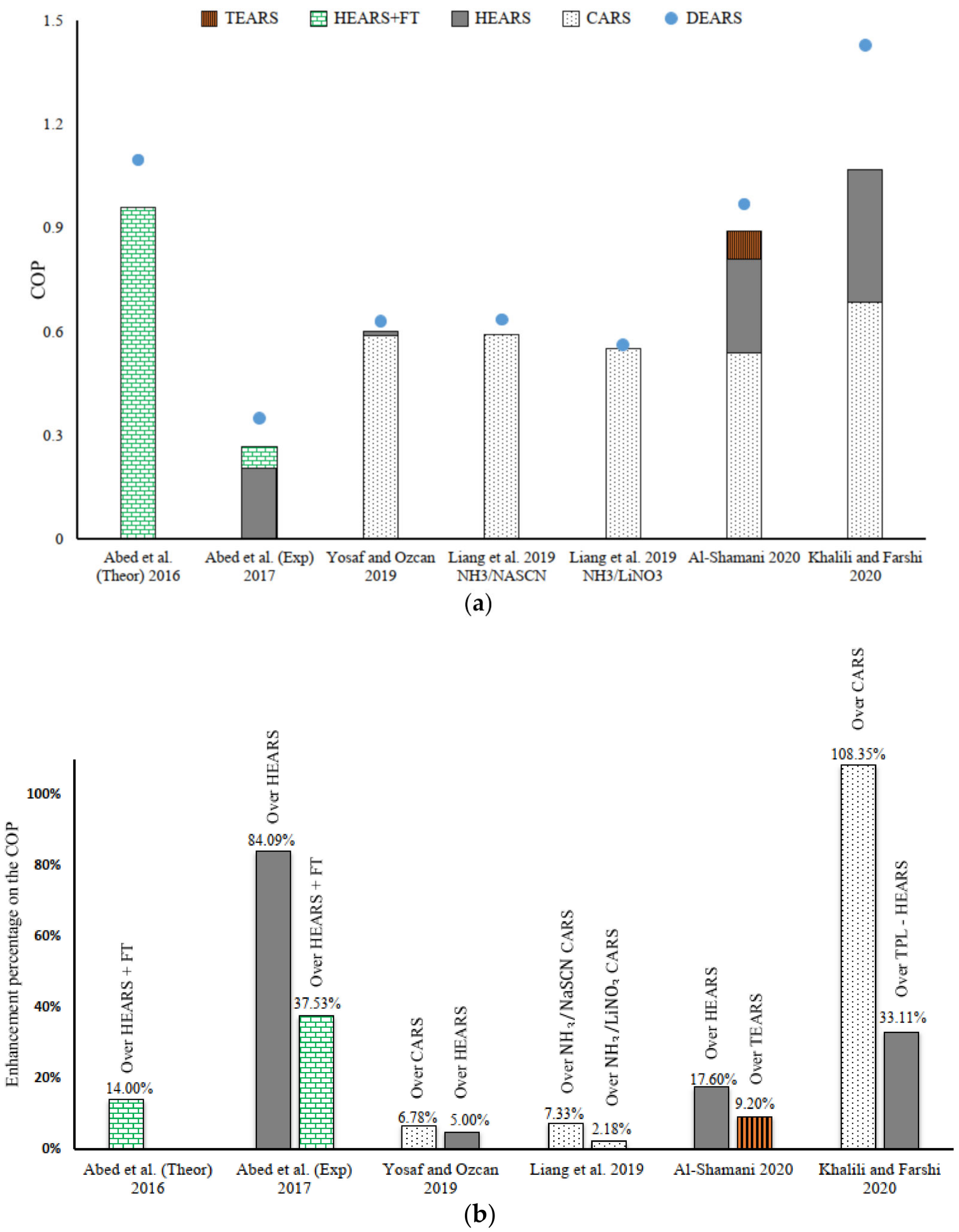


Figure 16. (**a**) Comparison between different configurations of DEARS and different absorption refrigeration systems; (**b**) improvement percentages of DEARS over various configurations of absorption refrigeration systems.

Among the five identified DEARS, four were theoretically studied, whereas the only experimental investigation on DEARS was conducted by Abed et al. [51]. Although this experimental setup achieved an average COP of 0.35, this value was 37.5% and 84% higher compared to the COP of the HEARS with and without a flash tank, respectively (Figure 16b).

Table 1 summaries the recent studies on dual-ejector absorption refrigeration systems. In order to make use of the ejector feature, it is preferable to the ARS to operate at higher pressures. This explains the tendency to use the ammonia-based solutions in multi-ejector ARS (Table 1), rather than other solutions such as $H_2O/LiBr$ and $H_2O/LiCl$.

Table 1. Summary of the studies on dual-ejector absorption refrigeration systems reported in the literature.

Study	No. of Ejectors	Locations/ Configuration	Working Solution	Advantages	Remarks
Abed et al. [73] (2016)	2	Upstream of the condenser	NH_3/H_2O	COP was between 11–14% higher compared to single ejector absorption cycle with flash tank (the thermal loads of both the generator and the condenser are always lower after using the second ejector).	T_g = 80–95 °C A third ejector is recommended to be used in raising the absorber pressure.
Abed et al. [51] (2017)	2	Upstream of the condenser	NH_3/H_2O	Dual-ejector system had the best performance among the three tested configurations (single ejector system and single ejector–flash tank system) as it achieved the lowest thermal loads in the generator, as well as the highest cooling effects. The use of a second ejector works as a flash tank assistance for improving the refrigerant quality that flows to the evaporator.	Tg = 80–95 °C, Flash tank is used. Several experimental limitations: low efficiencies during startup and transient conditions, long time to reach targeted operating conditions. ON/OFF operation drastically decreases the COP. Importance of distillation column design inside the generator. The use of Nano-fluids is recommended for future research.
Yosaf and Ozcan [44] (2019)	2	Upstream of the separation tank Upstream of the absorber	NH_3/H_2O	At increased absorber pressure the performance of the DEARS was better than what TPL-ARS offers (where only one ejector is used and located at the absorber inlet). Lower circulation ratio compared to the conventional system	Tg = 70 °C As the density of the lithium chloride solution is high, and the generator pressure of these working fluids is low (3–10 kPa), the pressure recovery in the solution ejector is negligibly small for these working fluids; therefore, the DEARS was only investigated for NH_3/H_2O.
Liang et al. [75] (2019)	2	Upstream of the absorber Downstream of the Absorber	$NH_3/LiNO_3$ $NH_3/NaSCN$	Utilizing air-cooled absorber and dual ejector assists in designing miniaturized and simplified systems and broadens the range of suitable operating conditions. Max COP = 0.6354	T_g = 75–125 °C Solution temperature at absorber outlet and the pressure ratio of the liquid–vapor are key factors. COP decreases as the system sacrifices part of the refrigerant in the steam-driven jet pump. Experimental study was recommended.

Table 1. *Cont.*

Study	No. of Ejectors	Locations/ Configuration	Working Solution	Advantages	Remarks
Al-Shamani [74] (2020)	2/3	Upstream of the condenser	NH_3/H_2O	The dual-ejector configuration outperformed the triple-ejector configuration by 5% and 9% at lower and higher generator operating conditions, respectively.	T_g = 70–90 °C The enhancement is due to reduction in the circulation ratio and improvement in the refrigerant quality at the evaporator inlet. The booster in triple-ejector cycle pushes the flow toward the constant section of the third ejector and, hence, decreases the flow and entrainment ratio of ejector-3
Khalili and Farshi [76] (2020)	2	Upstream of the condenser	NH_3/H_2O	The multi-pressure level cycle had a better performance over both conventional and TPL cycles. T_g in the new proposed cycle was in a range similar to that in the basic absorption cycle, but 36 to 55 °C lower than TPL cycle. Initial evaporator temperature in this DEARS was considerably low. This is reflected in capability of this cycle to produce refrigeration up to −24 °C.	T_g = 100 °C For analyzing the flow inside the vapor ejector, the shock circle approach was considered instead of one-dimensional method. The exergy destruction in the absorber represented 38~45% of the total. The remaining percentages are distributed over the liquid ejector, the cooling set, the desorber, and the SHE.

4. Coefficient of Performance of Hybrid Ejector-Absorption Refrigeration Systems (COP_{HEARS})

A typical single-effect ARS requires a driving temperature in the range of 70–95 °C and achieves a COP between 0.5 and 0.7, whereas a typical double-effect ARS has a COP between 0.8 and 1.2, but it needs a driving temperature that ranges between 120 and 150 °C [77]. Those values of COP are too small in comparison to the COPs of vapor compression refrigeration systems. Several studies claimed that single-effect ARS is capable to achieve a COP greater than unity when an ejector is added to the basic absorption cycle [57,78]. The vast majority of the studies reviewed in this paper calculated the COP as the ratio between the useful thermal energy output in the evaporator (Qe) and the heat input (Qg) plus the pumping work (Wp). Some studies included additional power consumed by components in their design such as booster [73] and small compressor [76]. Thus, the input power of these miscellaneous components (Wm) was added to the denominator in the below equation of COP. It is worth mentioning that none of the reviewed studies considered the energy consumed by the fans used in the heat exchangers. However, for absorption systems that utilize air-cooled heat exchangers, it is important to take into consideration the energy consumed by the fans when evaluating the overall system performance. Ignoring the power consumed by fans can lead to inaccurate calculation of the COPs.

$$\text{COP} = {}^{Qe}/_{(Qg + Wp + Wm)}$$

However, the majority of the available HEARS studies were theoretical studies carried out through mathematical modeling by applying thermodynamics laws and the use of computer software. In addition, those high values of the COP were obtained at particular or narrow ranges of operating conditions. The highest COP_{HEARS} values were obtained at high evaporator temperatures and low condenser temperatures. However, some operating conditions were impractical. For instance, R. Sirwan et al. [68] obtained a COP_{HEARS}

of 1.14 but at evaporation temperature equal to 14 °C, which seems inappropriate for either refrigeration or cooling applications. Similarly, Bellos and Tzivanidis [78] claimed that a COP_{HEARS} up to 1.65 is achievable at evaporation temperature of 12.5 °C, but at high generator temperature (T_g = 246 °C). This driving temperature is extremely high and unfeasible for single-effect ARS. The experimental studies of the HEARS revealed lower values of maximum COP_{HEARS}. At the same generator temperature, Abed et al. [51] increased the COP_{HEARS} from 0.29 to 0.46 by adding a flash tank. Y. Shi et al. [55] achieved a COP_{HEARS} of 0.87 but for double-effect configuration at a generator temperature of 200 °C. A higher value could be obtained at a lower generator temperature (T_g = 135.5 °C) when Yan et al. [56] built and operated a variable effect HEARS that achieved a COP of 0.905. The theoretical COP_{HEARS} of this system was 0.98.

In the literature, the NH_3/H_2O LPC-HEARS was only studied in a single-effect configuration. Figure 17 shows the general trends of the COP of different hybrid ejector-absorption refrigeration systems. The two graphs below (Figures 17 and 18) were drawn by reproducing the data that were collected and generated in the studies, as indicated in the figures. The operating conditions in the evaporator were between −5 and 5 °C for NH_3/H_2O systems and between 5 °C and 10 °C for $H_2O/LiBr$ systems. The condenser temperature ranged between 30 °C and 40 °C for all cases. According to the graph in Figure 17, the NH_3/H_2O HEARS operates at a generator temperature range similar to that of the CARS. Simple NH_3/H_2O HEARS showed a COP trend similar to that of the CARS. To improve the COP, a flash tank could be added, while adding a flash tank and RHE revealed the best performance among other single-effect NH_3/H_2O LPC-HEARS.

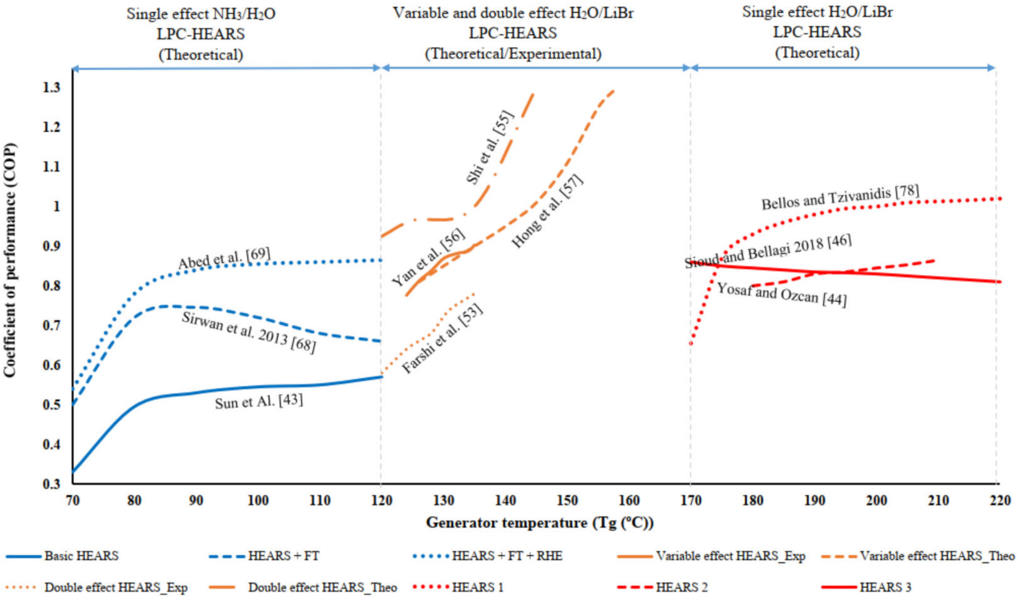


Figure 17. Change of the Coefficient of Performance (COP) with generator temperature (T_g (°C)) for different HEARS' configurations.

For a generator temperature in the range of 120–170 °C, variable- and double-effect configurations were investigated. The experimental and theoretical studies of the variable-effect HEARS revealed an identical, incremental trend with the generator temperature, whereas the double-effect HEARS showed a similar trend but with some divergence between the theoretical and experimental studies. To the best of the authors' knowledge, no study addressed triple-effect HEARS. In addition to its complex design, it requires generator temperatures over 180 °C. Additionally, for single-effect $H_2O/LiBr$ LPC-HEARS, S. Yosaf and H. Ozcan [44] claimed that the circulation ratio increased considerably if the system was operated at the typical generator temperatures of 70–100 °C. Correspondingly, the system performed better at higher generator temperatures of 170–220 °C. A similar claim was also stated by Jelinek and Borde [48]. However, such high operating temperatures in the generator should be avoided, as serious corrosion and thermal decomposition issues may arise when using the conventional H_2O/LiBr solution [61]. This issue explains why the performance of variable- and double-effect HEARS was only examined up to 170 °C, as shown in Figure 17.

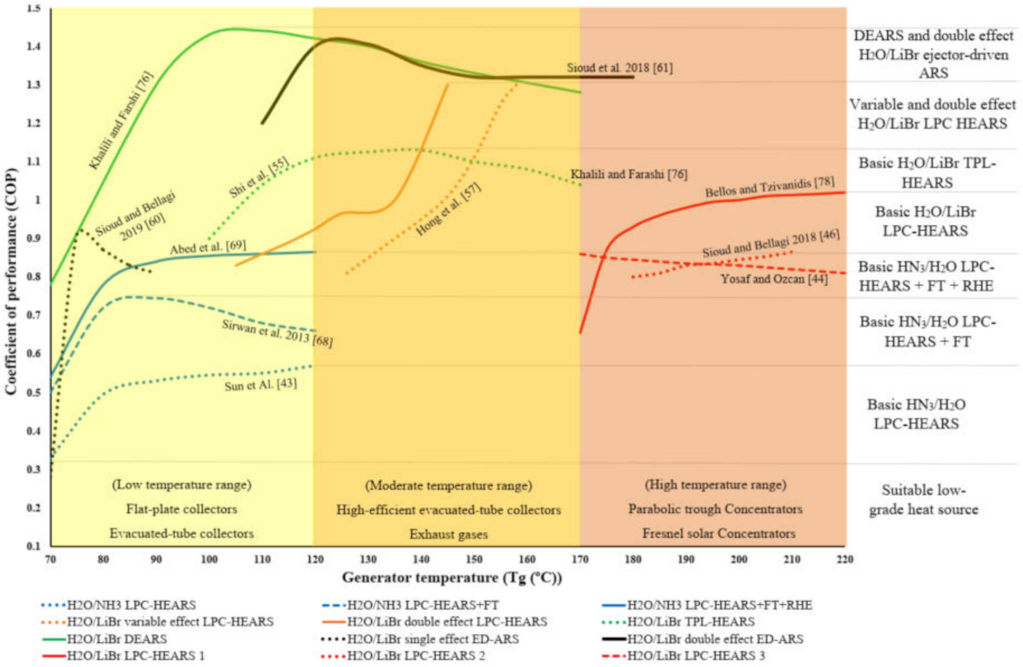


Figure 18. Range of maximum attainable theoretical COP values of various hybrid ejector absorption refrigeration systems.

Thus, adding an ejector to ARS improved the COP of the system. To obtain further improvement of the system performance, a flash tank and/or RHE could also be utilized. However, regardless of the added components or the type of the working solution, the COP of single-effect HEARS merely exceeded 1 unless upgrading the system configuration. According to the theoretical studies that are indicated in Figure 18, the COPs of variable- and double-effect HEARS range between 0.82 and 1.3 at the moderate range of the generator temperature of 120–170 °C. Yet, such upgraded configurations were only studied in the LPC design and solely for H_2O/LiBr solution. Thence, to obtain higher COPs, it is recommended to conduct investigations on variable- and double-effect TPL-HEARS with other alternatives of working fluids such as NH_3/H_2O and H_2O/LiCl. Among the different types of the hybrid systems, the best performance was achieved by the single-effect NH_3/H_2O DEARS and double-effect ejector-driven H_2O/LiBr ARS. The COPs of the two systems ranged between 1.2 and 1.46 under a generator temperature between 90–170 °C.

Figures 17 and 18 show the general performance trend of the various hybrid ejector-absorption systems as reported in the literature. On the right axis of Figure 18, various types of hybrid systems are sorted in ascending order according to the maximum obtainable COP by each system. Hence, the upper system has the higher maximum attainable COP. Moreover, Figure 18 shows the generator temperature required by each system and the possibility of using a low-grade heat-driving system. As depicted in Figure 18, the operating condition of the generator can be classified into three categories, low-temperature range of 70–120 °C, moderate-temperature range of 120–170 °C, and high-temperature range of 170–220 °C. Figure 18 shows that, even at a low-temperature range, the single-effect H_2O/LiBr DEARS outperformed the single-effect NH_3/H_2O HEARS with flash tank and RHE (the upper green line in the graph). Khalili and Farshi [76] argued that H_2O/LiBr HEARS can achieve a COP of above unity under moderate-temperature range if the system is designed in TPL configuration instead of LPC configuration (the lower green line). Finally, the LPC configuration requires an extremely high source temperature. The use of flash tank and RHE in HEARS at a temperate generator temperature (70–120 °C) is recommended. At a higher generator temperature (120–170 °C), the system with less complexity and the best performance is DEARS. Nevertheless, if the heat source temperature is variable, the performance of the DEARS might drop significantly. Thence, the variable-effect HEARS is considered the best alternative.

5. Integration of HEARS with Different Power Systems

Several studies demonstrated the notable outperforming of HEARS over the conventional ARS. Recently, the researchers directed to assess the practicability of integrating HEARS with different power generation systems. In spite of the fact that the use of an ejector adds a sort of complexity, yet, the merits outweigh. Wang [79] performed a parametric study of a Rankine power cycle integrated with LCP-HEARS in order to specify the pivotal operating parameters for the combined system. The combined cycle achieved greater refrigeration effect compared to the conventional combined power refrigeration cycle by approximately 10%. However, the turbine net output power remained the same. Hence, the thermal and exergetic efficiencies slightly increased. The inlet conditions at the turbine and the temperature at the heat source, condenser, and evaporator, as well as the solution concentration, had a major influence on the output and the exergy efficiency of the combined cycle. Finally, the authors recommended the implementation of experimental investigation.

Moreover, the Kalina cycle is another type of power cycle that is convenient, with HEARS, to configure such an integrated system. The thermodynamic modelling executed by Rashidi and Yoo [80] for combined Kalina-HEARS showed that the refrigeration effect and the thermal efficiency improved by 13.5% and 17%, respectively. In comparison with the expansion valve, the ejector enhanced the performance of the combined cycle by reducing the pressure drop and recovering a considerable portion of the evaporated working solution, thus increasing the mass flow rate delivered to the evaporator.

On the other side, Al-Hamed and Dincer [70] proposed a multi-generation, concentrated solar-geothermal integrated system in which a HEARS could operate efficiently. The multi-generation system was designed to serve a small community application. For such a community in the Yukon Territory the proposed system could effectively cover the whole demands of electricity, domestic hot water, and space heating and cooling. The parametric studies revealed that HEARS outperformed the conventional absorption system in terms of energetic coefficient of performance (COP or COP_{en}) and exergetic coefficient of performance (COP_{ex}). The term energetic is used to differentiate between the common COP calculated from the energy analysis and the COP obtained using exergy analysis. Moreover, the HEARS required lower mass flow rates than the conventional system. This advantage was a key factor to design a miniaturized system. Hence, when an absorption refrigeration system is utilized in a multi-generation system, it is essential to incorporate an ejector into the refrigeration system, particularly at high refrigeration loads, as the superiority of HEARS becomes more obvious [70]. Figure 19 shows the variation of the energetic COP (COP_{en}) with the entrainment ratio (ω) and the total pressure lift (r_p) in the HEARS. The latter parameter (r_p) was defined as the ratio between the back pressure and the pressure of the secondary fluid. Hence, it is dimensionless [70]. It could be observed that the least COP_{en} is obtained when the HEARS behaved just like the conventional refrigeration system.

Furthermore, Toghyani et al. [81] proposed and theoretically investigated the use of a proton exchange membrane (PEM) fuel cell to drive HEARS. The authors believed that the PEM could effectively drive the HEARS with overall system efficiency of 32–40% at a current density between 0.75 and 0.5 A/cm^2. Noteworthy, at higher current densities the voltage loss increases, thus the efficiency of the fuel cell decreases, consequently, the overall efficiency of the integrated system declines.

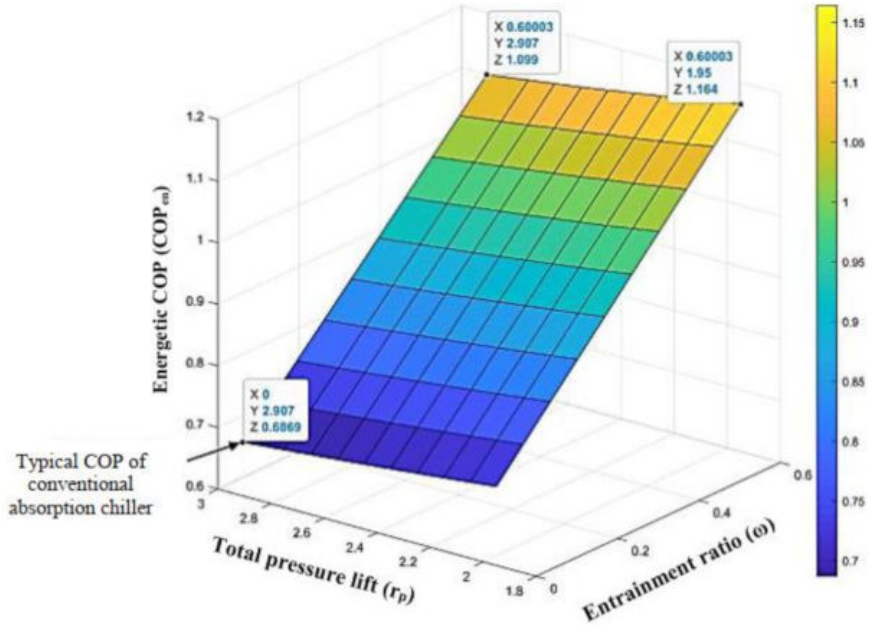


Figure 19. Variation of the energetic COP (COP$_{en}$) with entrainment ratio (ω) and total pressure lift (r_p) [70].

Differently, Yari et al. [82] proposed the integration of CARS with an ejector expansion cycle (EEC). Three configurations of the ARS were proposed: single-effect, double-effect parallel flow, and double-effect series flow. Following the first and second laws of thermodynamics, the three integrated systems were analyzed. The highest COP was obtained by integrating the double-effect parallel flow ARS with the EEC. Nevertheless, the integration of the single-effect ARS with the EEC was preferred, due to less system complexity with reasonable exergy efficiency and a COP of 1.182 at moderate generator temperature.

6. Future Opportunities to Improve Hybrid Ejector-Absorption Refrigeration Systems

The following is a summary of the future research opportunities identified from the previously discussed sections.

- The studies about multi-ejector absorption refrigeration systems are scarce. Moreover, the majority of the existing studies were theoretical. Hence, there is a necessity for experimental investigations.
- In LPC-HEARS, there is uncertainty about the capability of the steam ejector to handle low-density vapors. Therefore, adequate investigations on the viability of using low-density refrigerant vapor like water vapor are recommended [21].
- The integration of HEARS with power cycles was only implemented for LPC configuration. The studies showed a 10–13% increase in the refrigeration effect and a negligible effect on the net output power [79]. Consequently, it is recommended to conduct future investigations on the performance of the combined cycles when TPL-HEARS or DEARS are used.
- The fluctuation in the ejector performance is considered a serious challenge. It significantly deteriorates the performance of the HEARS. The utilization of adjustable ejectors becomes essential. In turn, this might add more cost to the absorption refrigeration machine since more sophisticated control devices will be required. Moreover, the need for miniaturized, yet more effective, heat exchangers is crucial. Subsequently, it is important to come up with special designs of heat exchangers that are compatible with ejector performance within the operating conditions of absorption refrigeration systems.
- Despite the claim that crystallization is avoided as the generator operates at a higher pressure [48], the risk of crystallization should be addressed in HEARS that use H_2O/LiBr and operate at high generator temperatures. Higher generator temperatures

increase the concentration of the solution to a degree that might result in precipitation of the LiBr. This issue was not taken into consideration in some previous studies such as [43,78].

- To the best of authors' knowledge, no one has investigated the progression of the absorption process when an ejector is located at the entrance of different types of absorbers such as falling film adiabatic absorber, microchannel absorbers, tubular bubble absorber, and the two types of the membrane-based absorbers, as well as other custom-designed absorbers. The pressure recovery attained by the ejector might be a solution to the relatively high pressure drop associated with the hollow fiber membrane contactor. Thus, efficient absorption processes can be achieved through compact absorbers. According to the recent review done by Seghal et al. [77], both bubble absorbers and spray absorbers were reported to outperform falling film absorbers. Consequently, those two designs might be prioritized.
- The study of absorption process progress in the aforementioned designs is better to be investigated in the case of working fluids. To identify the best combinations of absorber designs and solution alternatives, different binary and tertiary solutions, as well as solutions with additives and nanoparticles, are recommended to be utilized.
- The viability of operating a single-effect $H_2O/LiBr$ HEARS under generator temperatures between 70 °C and 170 °C should be investigated. Additionally, there is a lack of studies about variable- and double-effect NH_3/H_2O HEARS. The investigations should be conducted theoretically and experimentally for both single ejector and dual ejector ARS.
- Finally, a commercial company presented a two-step evaporation–absorption technology in which the evaporator and absorber were divided into two sections. The technology is used in commercial absorption chillers. The company claimed that the new design enhances the absorption process significantly and saves 10% of energy consumption in comparison with the conventional "single-step" design [83]. In future work, two-step evaporation–absorption technology will be examined in an absorption refrigeration system where two ejectors will be incorporated to form DEARS (Figure 20). The evaporator, as well as the absorber, will be divided into parts (upper and lower sections). Different layouts of the refrigerant path lines will be investigated to identify the configurations with the highest performance.

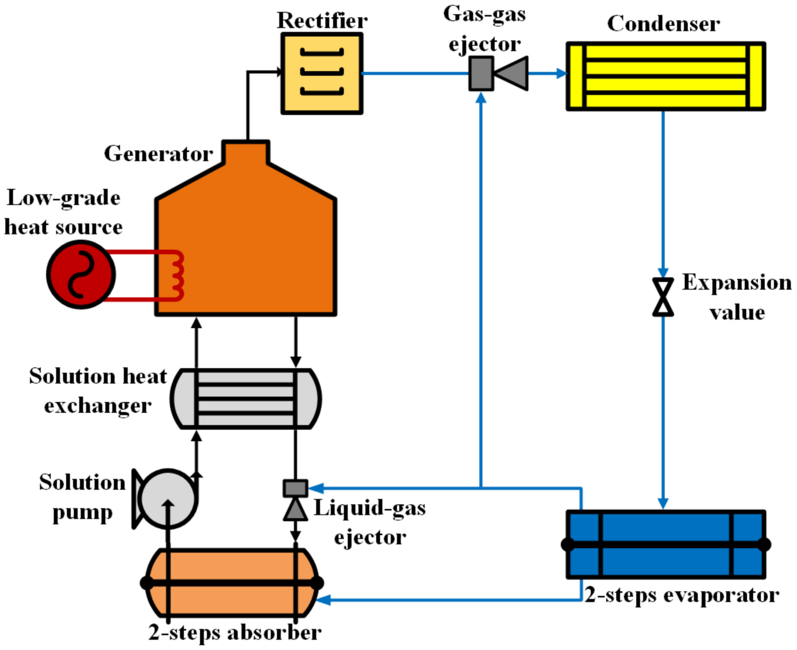


Figure 20. Proposed dual-ejector absorption refrigeration system (DEARS) with two-step evaporation–absorption technology.

To minimize the size of the system, the condenser and the absorber could be air-cooled, as the water-cooled condensers and absorbers utilize other auxiliary systems such as cooling towers and pumps. The system shown in Figure 20 may also require a few more power-consuming components such as a booster or a small compressor. Subsequently, to obtain accurate values of the COP, the energy consumption by the fans in the condenser and the absorber (W_f), in addition to other energy consumption by any other miscellaneous component (W_m), must be included in the evaluation of the system COP. Hence, the COP is calculated as follows:

$$\mathrm{COP} = {}^{Qe}/_{(Qg + Wp + Wf + Wm)}$$

where

$$Q_e = \left(\dot{m}C_p(T_{in} - T_{out})\right)_{evaporator}$$

$$Q_g = (\dot{m}C_p(T_{in} - T_{out}))_{heat\ source}$$

$$W_p = (\dot{m}(h_{out} - h_{in}))_{pump}$$

$$W_f = (VI)_{fan}$$

$$W_m = \sum (\dot{m}(h_{out} - h_{in}))_{\text{miscellaneous}}$$

7. Conclusions

The incorporation of an ejector into the absorption refrigeration cycle constitutes a hybrid ejector absorption system (HEARS) that operates at three pressure levels instead of two levels of the basic absorption refrigeration cycle. This characteristic improved one or two of the main heat and mass transfer processes in the cycle depending on where the ejector was located. The low pressure condenser (LPC-HEARS) configuration was found more prevalent than the triple pressure level (TPL-HEARS) configuration. This review included a meticulous elaboration of the improvements in the ARS performance through the utilization of ejectors.

Adding an ejector to NH_3/H_2O ARS was dysfunctional unless it coincided with the use of a flash tank (FT) and a refrigerant heat exchanger (RHE). A single-effect LPC-HEARS that uses $H_2O/LiBr$ working fluid was claimed to better operate at a high generator temperature range of 170–230 °C. However, such high operating temperatures should be avoided, as serious corrosion and thermal decomposition issues may arise for the conventional $H_2O/LiBr$ solution. TPL-HEARS, as well as variable- and double effects $H_2O/LiBr$ LPC-HEARS, were capable to attain a COP above unity at a moderate generator temperature range of 120–170 °C. In turn, the best performance was recorded for dual ejectors-absorption refrigeration systems (DEARS) and double-effect ejector-driven absorption refrigeration systems (ED-ARS), since their theoretical COP ranged between 1.2 and 1.46 within a wide range of generator temperature of 90–160 °C. Similarly, Figure 16 revealed that DEARS systems always outperformed the conventional ARS and the other corresponding configurations of hybrid ejector-absorption refrigeration systems.

Figures 17 and 18 accumulate the data available in the studies that were conducted on the various types of hybrid ejector absorption refrigeration systems. Figure 18 shows the general performance trend of the various hybrid ejector-absorption systems. It also shows the maximum attainable COP by each type of the hybrid system. It was argued that $H_2O/LiBr$ HEARS can achieve a COP of above 1 under moderate temperature range if the system is designed in TPL configuration instead of LPC configuration. At a higher generator temperature of 120–170 °C, the system with less complexity and the best performance was DEARS. However, if the temperature of the heat source is fluctuating, the performance of the DEARS might drop significantly. Thence, the variable-effect HEARS is considered to be the best alternative, particularly if an adjustable ejector is utilized. Generally, experimental investigations on HEARS and DEARS are scarce. Triple effects HEARS were neither investigated experimentally or theoretically.

On the other hand, it was observed that the innovative design of absorbers, desorber, and heat exchangers could miniaturize the size of the system and boost the heat and mass transfers. Membrane-based absorbers and desorbers were found to have the potential to reduce the system size while maintaining the efficient performance of the system. The high area-to-volume ratio is the most distinctive feature of these membrane contactors. Incorporating ejectors into ARS enhances evaporation, condensation, and absorption processes. Moreover, it reduces the required circulation ratio, which in turn permits the fabrication of miniaturized, less expensive, and more efficient systems. Therefore, the combination of utilizing ejectors and the use of membrane-based components is vital. Finally, this review showed that the absorption refrigeration systems have adequate utilization potential, opportunities of several development aspects, and chances of smart integration with various power systems. As detailed in Section 6, a number of research gaps were identified and recommended for future work. The authors believe that the recommended aspects could lead to significant improvements in absorption refrigeration technology.

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Abbreviations

ARS	Absorption refrigeration system
C	Specific heat capacity
CARS	Conventional absorption refrigeration system
COP	Coefficient of performance
DEARS	Dual ejector absorption refrigeration system
DX	Direct expansion
Ej	Ejector
FG	Flanged ball
FT	Flash tank
h	Specific enthalpy
HE	Heat exchanger
HEARS	Hybrid ejector absorption refrigeration system
I	Electrical current
LPC	Low pressure condenser
P	pressure
Q	Heat rate

RHE	Refrigerant heat exchanger
SHE	Solution heat exchanger
T	Temperature
TEARS	Triple ejector absorption refrigeration system
TPL	Triple pressure level
TV	Throttling valve
W	Work
V	Voltage
$\dot{m}$	Mass flow rate
Subscripts	
a	Absorber
c	Condenser
e	Evaporator
g	Generator
r	Refrigerant
s	Solution
in	Inlet
out	Outlet

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