A review of absorption heat transformers

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HIGHLIGHTS

• We review heat transformer systems in papers that were mainly published in specialized journals.
• We cover single stage, advanced systems, applications and new working pairs.
• 168 references were classified and cited.
• Tables were provided mentioning the author, the working pairs and the relevant implications.
• Conclusions were provided for the state of the art of heat transformers.

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ABSTRACT

In this paper, a review of the performance and development of absorption heat transformers is presented. The review covers the current state of theoretical and experimental studies of single and advanced systems, operating with conventional or alternative mixtures. It also includes their applications, such as waste heat recovery from industrial processes, cogeneration systems and seawater desalination and distillation among others. A bibliographic review has been done based on international journals, dating back from 1986 to date. The review does not intend to be exhaustive, but to reflect the most important research that has been published concerning these technologies.

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Contents

1. Introduction .............................................. 655
2. Theoretical studies ..................................... 655

2.1. Single-stage heat transformers .......................... 655
2.1.1. Description ......................................... 655
2.1.2. SSHT operating with water/lithium bromide ...... 656
2.1.3. SSHT operating with alternative mixtures ....... 656
2.1.4. Conclusions of SSHT ............................... 657
2.2. Advanced absorption heat transformers ................. 657
2.2.1. Description of advanced systems .................. 658
2.2.2. Advanced AHT operating with water/lithium bromide 658
2.2.3. Advanced AHT operating with alternative mixtures 659
2.2.4. Conclusions of AAHT ............................. 660
2.3. Heat transformers applications ........................ 660
2.3.1. Water purification .................................. 660
2.3.2. Energy recover from industrial processes ....... 661
2.3.3. Other applications ................................. 662

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1. Introduction

Energy is an essential element for economic development and social progress in all countries. Without adequate and secure supplies of energy, objectives of economic and social development are unlikely to be met. Currently, crude oil, natural gas (NG) and coal account for about 90% of the world’s commercial energy production. The rest is provided by a variety of sources which include nuclear power, geothermal energy and renewable resources.

Although in the last months, the cost of energy has been reduced considerably due to an oversupply, it is not clear that the prices of oil and natural gas will remain low in the upcoming years. In addition to, the use of fossil fuels continues to cause an increase in the emission and release of CO₂ into the atmosphere. It is not surprising then, that many countries are investing important amounts in the development of equipment to facilitate the recovery and efficient use of energy.

Some of the most interesting devices for energy savings, which consume negligible amounts of primary energy, are heat-driven absorption heat-pump systems. These and especially absorption heat transformers are some of the most promising devices for upgrading industrial waste heat and heat from geothermal and solar sources to higher temperature levels. Moreover, heat transformers can be used in cogeneration systems, for seawater desalination and distillation among other applications.

Absorption heat transformers (AHT) are devices for increasing the temperatures of moderately heat sources to more useful levels. Typically, with single-stage systems up to half of the heat supply could be increased in temperature while the rest is discharged to the atmosphere at lower temperature. Currently, two bibliographic reviews about heat transformers have been published in international journals. Parham et al. [1] published a comprehensive review of 99 references of single and advanced absorption heat transformers and their applications in different industrial processes reporting, for some cases, economic aspects. Donellan [2] analyzed 106 references on the vapor absorption heat transformers emphasizing in optimization studies, alternate cycle configurations, some studies of working fluids and industrial application case studies.

The present paper is a comprehensive bibliographic review of the state of the art of AHT. The review covers the current state of theoretical and experimental studies of single and advanced systems, operating with conventional or alternative mixtures. It also includes their applications, such as waste heat recovery from industrial processes, cogeneration systems, seawater desalination and distillation, among others. The bibliographic review was done based on international journals, dating back from 1986 to date. The review covers 158 studies related on absorption heat transformers. It does not intend to be exhaustive, but to reflect the most important research that has been published concerning these technologies.

2. Theoretical studies

This section presents everything in reference to theoretical studies regarding heat transformers including the description and research of the main cycles, either single-effect or advanced, as well as the use of conventional and alternative mixtures and their possible applications.

2.1. Single-stage heat transformers

2.1.1. Description

A single-stage heat transformer (SSHT) basically consists of an evaporator (EV), a condenser (CO), a generator (GE), an absorber (AB) and a heat exchanger (HE) or also called economizer as shown in Fig. 1. Waste heat is added at intermediate temperature to the generator (Q_{GE}) to vaporize the refrigerant from the weak solution (low absorbent concentration). The vaporized refrigerant goes to the condenser where it is condensed delivering an amount of heat (Q_{CO}) at low ambient temperature. The refrigerant leaving the
condenser is pumped to the evaporator where it is evaporated by means of a quantity of waste heat at intermediate temperature (Q_{AB}). After this, the refrigerant vapor goes to the absorber where it is absorbed by the solution with high concentration of absorbent coming from the generator, delivering an amount of heat at higher temperature (Q_{AB}). Finally, the solution with low concentration of absorbent returns to the generator, preheating the solution in the economizer starting the cycle again.

Some theoretical studies of SSHT independent of the used mixtures have been carried out by diverse authors. The optimal performance of an AHT was investigated by Chen [3,4]. He proposed a general expression related to the rate of heat pumping, the coefficient of performance (COP), and the overall heat transfer area of the heat transformer to optimize the main performance parameters of the AHT. Chen [5] also carried out a thermodynamic analysis of the performance of a solar absorption heat transformer (SAHT) to determine the maximum COP. The author reported that the results may serve as a good guide for the evaluation and optimization of existing SAHT. Bhardwaj et al. [6] carried out a finite time optimization of an irreversible AHT. The parametric study provided the variation of the maximum heating load, COP, working fluid temperatures and heat transfer rate between the system and its thermal reservoirs with operating variables. The performance of the generalized irreversible four-heat-reservoir AHT cycle with heat resistances, heat leak and internal irreversibility was analyzed and optimized using finite-time thermodynamics by Qin et al. [7]. Based on the same generalized irreversible heat transformer, Qin et al. [8,9] proposed a generalized heat transfer law to optimize the performance of the system. Based on an endoreversible absorption heat transformer cycle, Qin et al. [10] and Sun et al. [11] developed models which could be used to provide some guidance for the optimal design of absorption heat transformers, and Wu and Chen [12] carried out a parametric optimum design of an irreversible heat transformer based on the thermo-economic approach.

2.1.2. SSHT operating with water/lithium bromide

Eisa et al. [13] published the thermodynamic design data for an AHT operating with H_{2}O/LiBr reporting tables of possible combinations of operating temperatures, concentrations, flow ratios (FR) and COP. The authors found that the maximum COP was close to 0.5. A graphical exergy study on a SSHT was carried out by Ji and Ishida [14]. The results showed that the exergy losses in the pre-mixing process in the absorber was very large, reason why the authors proposed a multiple-compartment absorber in close-to-equilibrium operation, in order to reduce that exergy losses. Based on the second law of thermodynamics an analysis was conducted by Wang et al. [15] to study the effects of diverse parameters on the COP and irreversibility of the cycle. Zebar et al. [16] developed a mathematical model for an AHT operating according to the endoreversible cycle. The model was used to find out the optimal operating parameters using an alleged structural analysis. It was concluded that for the same thermal powers and heat transfer parameters, an increase on the first and second law efficiencies equal to 10% and 5.3%, respectively, could be achieved. Guo et al. [17] developed a mathematical model of a vertical falling film absorber to analyze the performance of AHT under design and off-design conditions. The results showed that the COP and exergy efficiency were significantly higher under off-design conditions compared with the use of previous operation strategies.

2.1.3. SSHT operating with alternative mixtures

To date, the H_{2}O/LiBr has been the most used mixture in AHT, even though it possesses some well-known disadvantages. For this reason, several studies have been carried out in order to find alternative mixtures to be used in heat transformers. George and Murthy carried out diverse studies on the performance of AHT operating with R21/dimethyl formamide (DMF) and R21/dimethylether tetraethylene glycol (DMETrEG) pairs. They found that the COPs using R21/DMF increased from 0.45 to 0.498 and using R21/DMETrEG from 0.41 to 0.442 when the mass transfer effectiveness in the absorber increased from 0.3 to 0.9 [18]. They also found that the COPs operating with R21/DMF increased from 0.445 to 0.479 and with R21/DMETrEG from 0.391 to 0.425 when the mass transfer effectiveness in the generator increased from 0.3 to 0.9 [19], and the COPs using R21/DMF varied from 0.417 to 0.509 and using R21/DMETrEG from 0.405 to 0.446 when the heat exchanger effectiveness varied from 0.3 to 0.9 [20]. In all the cases the generator and condenser temperatures where 90 °C and 30 °C, respectively. Also they studied the effect of the evaporator and generator temperatures on the system performance and found that the COP increases with the increment of both temperatures, especially when the higher temperature of the heat source was supplied to the generator [21]. In the four studies carried out by these authors, the system operating with R21/DMF achieved higher COPs than the system operating with R21/DMETrEG. A series of papers about the thermodynamic design data of AHT operating with different mixtures were published by diverse authors. Best et al. [22] reported the results of a SSHT operating with the NH_{3}/H_{2}O with COPs between 0.48 and 0.53, and the mixture with TEG-DME, respectively. A comparative study of different working fluids. From the analysis of these papers for an specific condition of 60 °C of the heat source the COP were 0.453, 0.443, 0.432, 0.422, 0.32 and 0.279 for water/lithium bromide, water/Carrol, water/tarnary hydrides, water/lithium iodide, ammonia/lithium nitrate, Patil et al. [25] water/lithium iodide, Best et al. [26] ammonia/sodium thiocyanate, Best and Rivera [27] water/Carrol™ (where Carrol is a mixture of LiBr and ethylene glycol [(C_{2}H_{5}OH)] in the ratio 1:4.5 by weight), and Rivera and Romero [28] water/tarnary hydrides. From the analysis of these papers for an specific condition of 60 °C of the heat source the COP were 0.453, 0.443, 0.432, 0.422, 0.32 and 0.279 for water/lithium bromide, water/Carrol, water/tarnary hydrides, water/lithium iodide, ammonia/sodium thiocyanate and ammonia/lithium nitrate, respectively. So, from this similar studies it can be concluded that the highest COP were obtained with mixtures using water as refrigerant. However, it was also observed that the highest gross temperature lifts (GTL) up to 60 °C were obtained mainly with mixtures using ammonia as refrigerant. Stephan and Seher [29] reported the results of a SSHT operating with the NH_{3}/H_{2}O mixture. The results showed that a COP and a GTL as high as 0.35 and 40 °C, could be obtained, respectively. Kriplani et al. [30] presented a comparative performance study of a SSHT operating with H_{2}O/LiBr, R21/DMF, R22/DMF and R22/DMETrEG as working fluids. It was found that for similar operating conditions the mixture with the higher COPs, between 0.48 and 0.60 was R21/DMF followed by H_{2}O/LiBr with COPs between 0.48 and 0.53, and the mixture with the lower COPs, between 0.35 and 0.44 was R/22/DMF. Ciambelli and Tufano [31–33] developed a model for an AHT operating with the water/sulfuric mixture. The results showed that the mixture was particularly suited for heat source temperatures higher than 100 °C. The maximum COP was almost 0.5. Tyagi et al. [34] studied the theoretical performance characteristics of SSHT using ammonia/1,4 butanediol, ammonia/2,3butanediol, ammonia/triethyleneglycol dimethyl ether (TEG-DME) and sulphur dioxide/dimethylacetamide (SO_{2}/DMA). For a heat source temperature of 60 °C, a condenser temperature of 30 °C and a Δx = 16% the COP were 0.593, 0.541, 0.503, 0.498 and 0.487 for the mixtures NH_{3}/H_{2}O, SO_{2}/DMA, NH_{3}/1,4 butanediol, NH_{3}/2,3 butanediol and NH_{3}/TEG-DME, respectively. A comparative study of different working fluid combinations with R22 as refrigerant and six absorbents, namely, dimethyl formamide (DMF), dimethyl acetamide (DMA), 1,2-pyridylidone (NMP), dimethylether tetraethylene glycol (DMETrEG) and dimethylether triethylene glycol (DMETrEG) in a vapor absorption heat transformer was carried out by Fatouh and Murthy [35]. It was found that the DMA and NMP were preferable solvents for R22 to...
obtain high heat delivery temperatures, low circulation ratios and high COP which were around 0.4. Zhuo and Machielsen [36] compared the performance of an AHT using the working pair trifluoroethanol/pyrrolidone (TFE/Pyr) with the H2O/LiBr. The results showed that the useful heat and the COPs were up to 20% higher with the working pair H2O/LiBr than with TFE/Pyr. However due to corrosion problems the H2O/LiBr could only operate at temperatures up to 150 °C, while the alternative mixture could operate up to 200 °C. Ismail [37] studied the performance of AHT operating with the ammonia/water mixture. COP values as high as 0.45 were obtained at low GTL and heat exchanger effectiveness close to 0.9. Yin et al. [38] compared the theoretical performance of an AHT operating with H2O/LiBr, TFE (2,2,2-trifluoroethanol)/NMP (N-methyl-2-pyrrolidone), TFE/E181 (dimethylether tetra/ethylene glycol) and TFE/Pyr. The results showed that the COPs were higher with the mixture H2O/LiBr than those with the other mixtures, however, they found that with TFE/NMP, TFE/E181 and TFE/Pyr the system could operate up to 200 °C, instead of the 150 °C with the H2O/LiBr. Bourouis et al. [39] compared the performance of an SSHT operating with the H2O/(LiBr + Li + LiNO3 + LiCl) and H2O/LiBr mixtures. The multi-component salt mixture showed a considerably higher solubility and less corrosive than the H2O/LiBr mixture. The COP for the multicomponent salt were almost constant with the increase of the condenser temperature, while the COP with the H2O/LiBr decreased considerably. The maximum COP with the proposed mixture was 0.51. Zhang and Hu [40] reported the performance simulation of an SSHT using a new working pair composed of ionic liquids, water/1-ethyl-3-methylimidazolium dimethylphosphate (H2O/EMIM-DMP) and compared the results with the mixtures water/lithium bromide and water/trifluoroethanol (TFE) + tetraethyleneglycol dimethylether (E181). The results indicated that when generation, evaporation, condensing and absorption temperatures were 90 °C, 90 °C, 35 °C and 130 °C, the COP using H2O/LiBr, H2O/EMIM-DMP and TFE/E181 as working pairs were 0.494, 0.481 and 0.458, respectively. Jernqvist et al. [41] proposed different efficiencies to evaluate heat transformers operating with the H2O/NaOH pair. The maximum COP obtained with the mixture was 0.48.

2.1.4. Conclusions of SSHT

From the bibliographic review related to SSHT operating with the mixture of H2O/LiBr, it can be observed that most works have focused on the analysis of these systems from the point of view of the first and second laws of thermodynamics, in an attempt to find the optimum conditions to achieve the highest COP and exergy efficiencies, as well as the lowest irreversibilities. For this mixture the highest COPs were close to 0.5 with maximum GTL values of 50 °C.

With respect to the SSHT operating with alternative mixtures, many binary and even ternary options instead of the H2O/LiBr mixture have been analyzed. However, the only one with COPs higher than 0.5 were: the R21/DMF mixture with COPs of up to 0.6 [30] and the NH3/H2O and SO2/DMA mixtures with maximum COPs of 0.593 and 0.541, respectively [34]. Zhuo and Machielsen [36] and Yin et al. [38] found that with the TFE/Pyr, TFE/NMP and TFE/E181 mixtures it is possible to operate the SSHT at temperatures of up to 200 °C instead of the 150 °C, which can be achieved for systems using the H2O/LiBr mixture due to crystallization problems. In respect to the GTL it was found that the mixtures that use ammonia as a refrigerant can reach a GTL of up to 60 °C instead of the 50 °C obtained with the H2O/LiBr mixture [22,24,26]. Finally, Best and Rivera [27] and Bourouis et al. [39] reported that the ternary mixture H2O/Carrol™ and the quaternary mixture H2O/ (LiBr + Li + LiNO3+ LiCl) have a higher solubility and are less corrosive than the H2O/LiBr mixture.

2.2. Advanced absorption heat transformers

Advanced adsorption heat transformers (AAHT) refer to those systems that use more components than SSHT in order to achieve higher COP or GTL. Two-stage heat transformers and double-absorption heat transformers are some examples of advanced systems.
2.2.1. Description of advanced systems

Two-stage heat transformers (TSHT) basically consist of two SSHT, which can be coupled in three different ways as shown in Fig. 2. The first way is by connecting the absorber of the first stage to the evaporator of the second stage, so the heat delivered by the absorber allows the evaporation of the working fluid in the second stage \( Q_{AB1} = Q_{EV2} \). The second way is by coupling the absorber of the first stage to the generator of the second \( Q_{AB1} = Q_{GE2} \). The third way is by splitting the heat delivered by the absorber of the first stage between the generator and the evaporator of the second stage \( Q_{AB1} = Q_{EV2} + Q_{GE2} \).

Double-absorption heat transformers (DAHT) basically consist of a generator (GE), a condenser (CO), an evaporator (EV), an absorber (AB), an absorber-evaporator (AE) and a heat exchanger or economizer as shown in Fig. 3. A heat source is supplied to the generator \( Q_{GE} \) to separate the working fluid at an intermediate temperature \( T_{GE} \). The vaporized working fluid is condensed in the condenser at a lower temperature \( T_{CO} \). Then the condensed working fluid is split into two streams. One of them is pumped into the evaporator where it is vaporized at an intermediate temperature \( T_{EV} \) and pressure \( P_{EV} \). The other one is pumped at a higher pressure \( P_{AB} \) and vaporized in the absorber-evaporator by an amount of available heat \( Q_{AE} \). The vaporized working fluid is absorbed in the absorber, at a higher temperature \( T_{AB} \), by the high concentration solution \( X_{GE} \) coming from the generator. The diluted solution at an intermediate concentration \( X_{AB} \) is split into two streams. One goes to the generator preheating the high concentration solution through the heat exchanger. The other is fed to the absorber-evaporator absorbing the vaporized working fluid coming from the evaporator and delivering an amount of heat \( Q_{AE} \). Finally, the diluted solution at a low concentration \( X_{AE} \) leaves the absorber-evaporator and goes to the generator starting the cycle again.

Besides the double-absorption and the two-stage absorption heat transformers, there are also triple-absorption heat transformers (THAT), which are similar to the double absorption systems, but with an additional stage at higher temperature as can be seen in Fig. 4.

2.2.2. Advanced AHT operating with water/lithium bromide

A couple of studies on the thermodynamic analysis on single and advanced AHT operating with \( \text{H}_2\text{O}/\text{LiBr} \) were performed by Rivera et al.\[42,43\]. The results showed that SSHT systems were the simplest and most efficient, since they achieved a maximum COP of 0.48, while the maximum COPs were 0.32 and 0.31 for the DAHT and TSHT, respectively. However, the highest GTLs were obtained with the TSHT, followed by the DAHT and finally the SSHT, achieving GTL values of 80 °C, 75 °C and 50 °C, respectively. The authors concluded that because DAHT could achieve similar COP and GTL than TSHT, the former seemed to be a better alternative since they require less components and are less expensive. Ji and Ishida [44] proposed the modification of a conventional TSHT operating with \( \text{H}_2\text{O}/\text{LiBr} \) by utilizing the sensible and latent heat exchange-modes in the generators and absorbers. The results showed that with the modifications the GTL can be improved by 10.7 °C and the exergy efficiency can be increased from 48.14 to 54.95%, however, the COP decreased from 0.314 to 0.293. Based on the performance analysis of the SSHT, DAHT and TSHT a new ejection-absorption heat transformer (EAHT) with \( \text{H}_2\text{O}/\text{LiBr} \) was presented and analyzed by Shi et al. [45], (see Fig. 5). The proposed system incorporates an ejector at the entrance of the absorber in order to increase the pressure and temperature of the component. Compared with a conventional SSHT, the delivered useful temperature for the EAHT increased 5% and the exergy efficiency increased 2.7%, however, the COP decreased 0.4% for the discussed conditions. Donnellan et al. [46] studied a TAHT operating with \( \text{H}_2\text{O}/\text{LiBr} \). The results showed that the generator was the source of the greatest...
exergy destruction in the cycle, followed by the two absorber–evaporators. GTL as high as 140 °C could be obtained with the proposed systems but with COPs not higher than 0.2. Donnellan et al. [47] modeled a THAT using H2O/LiBr in order to determine the optimum number and locations of internal heat exchange units within the system. It was found that the conventional design of the TAHT does not employ heat exchangers effectively and by rearranging these components the system COPs could be increased by 11.7%. Strategically adding one or two extra heat exchangers the COPs were increased by 16.4% and 18.8%, respectively. Wang et al. [48] reported the optimization design of the large temperature lift/drop multi-stage vertical absorption temperature transformer operating with H2O/LiBr; the results showed that the minimum total multiplication of the heat transfer coefficient by the heat transfer area was obtained when entransy dissipation per transferred heat was uniformly distributed in the four basic components. The authors did not report values of the COP neither GTL for the proposed system. Based on first and second law of thermodynamics Fartaj [49], and Martínez and Rivera [50] analyzed a DAHT operating with H2O/LiBr. The authors concluded that second law analysis offers an alternative view of cycle performance and provides an insight that the first law analysis cannot. Also it was found that the generator was the component with the highest irreversibilities contributing to about 40% of the total exergy destruction in the whole system. The thermodynamic performance of a new type of DAHT operating with H2O/LiBr was studied by Zhao et al. [51,52] and Hao et al. [53]. In the proposed cycle the strong solution coming from the generator was split into two streams instead of the weak solution coming from the absorber as it was previously proposed by other authors [42,43]. The GTL with the new proposed configuration was between 5 °C and 10 °C higher than those with previous DAHT, but the COP decreased about 0.01 when compared with the other configurations.

2.2.3. Advanced AHT operating with alternative mixtures

Besides the published studies about the modeling of advanced absorption heat transformers (AAHT) operating with the H2O/LiBr mixture, there have been several studies related with the development of AAHT operating with alternative mixtures. Ziegler and Alefeld [54] reported a method by which the COP of advanced absorption cycles could be calculated easily if the efficiencies of single-stage systems are known. Also compared the performance of AAHT operating with the working pairs H2O/LiBr and NH3/H2O. They found that the COP for a DAHT were 0.31 and 0.27 for the H2O/LiBr and NH3/H2O, respectively. The theoretical performance of SSHT and DAHT using water/ammonia as binary mixture was studied by Stephan and Seher [55] and Tyagi [56]. The result showed that the highest COP was 0.35 with GTL of 60 °C. Cambelli and Tufano [57–59] analyzed the performance of single and AAHT operating with the water/sulfuric acid mixture. The results showed that with the two-stage configuration a COP of 0.35 and GTL of 75 °C could be achieved, while with the double-absorption configuration the COP and GTL were 0.32 and 65 °C, respectively. Iyoki and Uemura [60] compared the performance of a TSHT operating with H2O/LiBr + ZnCl2 + CaBr2) and the conventional H2O/LiBr mixture. At similar conditions, the highest COP with the alternative mixture was 0.32 instead of the 0.34 obtained with H2O/LiBr, however, the proposed mixture has a wider range of operating conditions than the H2O/LiBr mixture. High-temperature absorption heat transformers operating with Alkitrate as the working pair were investigated by Zhuo and Machielsen [61]. The results of SSHT, DAHT and TSHT were reported and compared with H2O/LiBr cycles. The COP of Alkitrate cycles were practically the same than those with H2O/LiBr cycles, under the same operating conditions. It was concluded that Alkitrate was especially useful for operating at high temperatures, of up to 260 °C, however, the proposed mixture was not recommended at condenser temperatures lower than 50 °C due to solubility problems. Single and advanced heat transformers operating with the water/Carrol mixture were analyzed by Best et al. [62] and Tufano et al. [63]. For a condenser temperature of 30 °C and a generator temperature of 80 °C, the highest COPs were 0.49, 0.32 and 0.31 for the SSHT, DAHT and TSHT respectively. The highest GTL for SSHT was almost 60 °C, while for TSHT and DAHT were around 105 °C. A thermodynamic study of a DAHT operating with the water/calcium chloride mixture was carried out by Barragán et al. [64]. GTLs up to 40 °C were achieved with COP close to 0.3. Rivera et al. [65] compared the performance of SSHT, TSHT and DAHT operating with the water/lithium bromide and the water/Carrol mixtures. Similar tendencies and values of the COPs were obtained in general for both mixtures, however, at specific conditions the gross temperature lifts with the H2O/Carrol were up to 15 °C higher than those obtained with H2O/LiBr. A mathematical model was developed by Scott et al. [66] of a multi-compartment H2O/NaOH AHT. In the proposed system the generator and evaporator were divided in different sections to operate at different temperatures. The results showed that COPs as high 0.495 could be obtained with the proposed system. A self-regenerated AHT with a generator-absorber heat exchanger (GAX) cycle using the new organic working pair 2,2,2-trifluoroethanol (TFE)/N-methylpyrroolidone (NMP) was proposed by Shiming et al. [67]. Some of the most important features of the proposed mixture were the absence of crystallization and the low working pressures; however, it had the disadvantage of requiring rectification. The COPs of the system varied between 0.17 and 0.21. Wang et al. [68] compared the performance of a TSHHT operating with H2O/LiBr, with TFE/NMP and with H2O/LiBr in the bottom cycle and TFE/NMP in the high cycle. The highest COP and GTL for the system operating with H2O/LiBr in both cycles were 0.3 and 80 °C, respectively. Although the maximum COP for the system operating with H2O/LiBr and TFE/NMP was 0.25, the GTL was 90 °C, and the maximum absorber temperature was 40 °C higher than that attained with H2O/LiBr. Zhao et al. [69,70] reported the thermodynamic performance of a new cycle named double-effect absorption heat transformer (DEAHT) using TFE/EM1 as the working fluid. This system is a combination of a double-stage and double-absorption systems (see Fig. 6). The results showed that, when the temperature in the high-pressure generator exceeds 100 °C and the GTL was 30 °C, the COP of the system was about 0.58, which was larger than the 0.48 of the SSHT, however, this increase was still less than 0.64 of the DEAHT using H2O/LiBr as the working fluid. Sözen et al. [71–73] developed mathematical models of an ejector-absorption heat transformer.
(EAHT) operating with the NH$_3$/H$_2$O mixture. Under the same operating conditions, the COP and exergy COP were improved by 14% and 30% respectively, by using the ejector when compared to an AHT without an ejector. Romero et al. [74] modeled an experimental TSHT operating with a ternary mixture of hydroxides based in sodium, potassium and cesium. The results showed that it was possible to achieve a GTL of 72 °C with a COP of 0.32. Barragán et al. [75] modeled a single and DAHT operating with the mixtures H$_2$O/ CaCl$_2$ and H$_2$O/LiCl. The maximum COPs were 0.49 and 0.44 for the H$_2$/OCl/$Ca$ and H$_2$/O/LiCl, respectively. The GTLs reported were lower than 50 °C for both mixtures. A thermodynamic study of a SSHT and a DAHT using new working pairs composed of ionic liquids (1-ethyl-3-methylimidazolium tetrafluoroborate [emim] [BF$_4$]) and 1-butyl-3-methylimidazolium tetrafluoroborate ([bmm][BF$_4$]) as absorbent and 2,2,2-trifluoroethanol (TFE) as refrigerant was carried out by Ayou et al. [76]. The maximum values of COP for the DAHT operating with the proposed mixtures were between 0.24 and 0.26 which were lower than those obtained with the H$_2$/O/LiBr mixture which were about 0.32; however, it was shown than the mixtures TFE/[bmm][BF$_4$]) and TFE/[emim][BF$_4$]) could achieve GTLs up to 15 °C higher than those obtained with the H$_2$/O/LiBr mixture.

2.2.4. Conclusions of AAHT

As can be seen from the bibliographic review there are several studies regarding the development of new heat transformers cycles. They have all focused on obtaining higher COPs or GTLs and centered in both the use of the H$_2$/O/LiBr and alternative mixtures. With respect to advanced cycles operating with the H$_2$/O/LiBr they have mainly focused in double-absorption, two-stage, triple-stage, ejection-absorption and double-effect absorption heat transformers. Of all the heat transformers analyzed, the DEAHT are the ones with the higher COP of up to 0.64, however their GTLs are the lowest of approximately 30 °C [69,70]. The SSHT reach COP values close to 0.5 with a GTL of 40 °C. The TSHT reach COP values of 0.32 with GTL values of up to 80 °C, while with the DAHT, COP values of 0.31 and maximum GTLs of 75 °C [42,43]. The TAHT systems reach GTLs of up to 140 °C, but COPs no higher than 0.2 [46]. With the ejection-absorption heat transformers 5% higher GTLs were obtained, but 4% lower COPs with respect to the SSHT under the same operating conditions [45]. Rivera et al. [42,43] and Gambelli and Tufano [57–59] concluded that the DAHT seemed to be a better alternative than TSHT since similar COP and GTL could be achieved with both systems.

With respect to the AAHT operating with alternative mixtures, from the bibliographic review it can be seen that there have been many mixtures analyzed, but with none one of them COP higher were obtained than those obtained with the H$_2$/O/LiBr mixture. However, regarding the GTL Rivera et al. [65] and Ayou et al. [76] analyzed the mixtures H$_2$/O/Carrol, TFE/[bmm][BF$_4$]) and TFE/([emim][BF$_4$]), respectively, and found that GTL up to 15 °C higher could be obtained with those mixtures than those with the H$_2$/O/LiBr mixture. Besides, Wang et al. [68] found that a TSHT operating with H$_2$/O/LiBr in the bottom cycle and TFE/NMP in the top cycle could reach absorber temperatures up to 40 °C higher than those obtained with the same system but utilizing H$_2$/O/LiBr in both cycles. In regard to solubilities, Iyoky and Uemura [60] reported that the mixture H$_2$/O/LiBe + ZnCl$_2$ + CaBr$_2$) has a wider range of operating conditions in a TSHT than the H$_2$/O/LiBr mixture. Zhuo and Machielsen [61] reported that for DAHT and TSHT the COP of Alkitrate cycles were practically the same than those of H$_2$/O/LiBr cycles, under the same operating conditions. However, they found that Alkitrate was especially useful for operating at high temperatures, up to 260 °C, but the proposed mixture was not recommended at condenser temperatures lower than 50 °C because of solubility problems. Finally, Fig. 7 shows the zones of COP against GTL for the different heat transformer configurations.

2.3. Heat transformers applications

Heat transformers can be used for different application such as: distillation in chemical plants, desalination or water purification, evaporation and waste heat recovery from industrial processes, among others.

2.3.1. Water purification

The integration of a water purification system and a heat transformer operating with the H$_2$/O/LiBr was modeled by Siqueiros and Romero [77], by Romero et al. [78] and by Contreras-Valenzuela et al. [79]. The results showed that the proposed system was not only capable to produce purified water but also to increase the system COP more than 120%, for some specific conditions, by recycling part of the energy from a water purification system. Escobar et al. [80] integrated the model of a helical double-pipe vertical evaporator into the thermodynamic model proposed by the previous authors in order to design physically this component. Romero and Rodriguez [81] developed a model of an AHT for water purification (AHTWP) in order to optimize its performance. It was found that with heat source temperatures between 65 °C and 80 °C it was possible to obtain absorber temperatures higher than 105 °C for water distillation, achieving COPs from 0.30 to 0.43. Also, for AHTWP mathematical models using artificial neural networks have been developed to predict the COP [82] and to find the optimal operating conditions [83]. Gomri [84] developed a model of a flat plate solar collectors, an SSHT and a desalination system used to provide a beach house located in Skikda with drinking water. The results showed that the water productivity varied between 0.64 l/h/m$^2$ and 0.62 l/h/m$^2$ depending on the operating conditions. Gomri [85] carried out a comparative study from the first and second law of thermodynamics between SSHT and DAHT operating with H$_2$/O/LiBr for seawater desalination. The results showed that when intermediate heat source temperature was supplied from 74 °C to 96 °C the maximum energy efficiencies were between 0.799 and 0.833, and from 1.276 to 1.308 for the SSHT and DSHT, respectively, while the exergy efficiencies varied from 46.9% to 54.1% for the SSHT and from 58.5% to 60.8% for the DSHT. Srinivas et al. [86] developed a mathematical model of an AHT coupled to a multi-effect desalination system operating with diverse working pairs. The results showed that the system operating with the H$_2$/O/
(LiCl + LiNO₃) mixture achieved the highest COP which was close to 0.5 and the lowest values of the energy consumed to produce 1 m³/h of distilled water, which varied between 128 and 134 kWh/m³. Rivera et al. [87] carried out energy and exergy analysis of a heat transformer for water purification increasing the heat source temperature operating with the H₂O/LiBr mixture. The results showed that the highest irreversibilities occurred in the absorber contributing with more than 30% of the irreversibilities of the entire system, followed by the auxiliary condenser with about 25%. The highest COP was almost 0.5. Alternative AHT configurations integrated with water desalination systems were studied by Parrham et al. [88]. It was shown that applying different modifications, the COP of the AHT could be increased to achieve values close to 0.55 and consequently increasing the productivity of the desalination system. The maximum rate of distilled pure water reached was 0.2435 kg/s. Juárez-Romero et al. [89] developed a dynamic model which described the heat and mass transfer of a horizontal pipe absorber applied to an AHT operating with H₂O/LiBr used for water purification. The authors concluded that the model could be used to optimize the performance of the system. A thermodynamic analysis of six different configurations of TAHT utilizing H₂O/LiBr integrated to a water desalination system was conducted by Khamboshi [90]. It was shown that modified configurations of TAHTs could increase the freshwater productivity compared to conventional systems. The results indicated that the optimized amount of distilled water produced was 0.1307 kg/s when a heat load of 1200 kW was supply to the heat transformer with a maximum COP of 0.25. The performance analysis on a new multi-effect distillation combined with an open H₂O/LiBr absorption heat transformer (OAHT) driven by waste heat was carried out by Zhang et al. [91]. The results indicated that combined with OAHT, the waste heat at 70 °C could be elevated to 125 °C producing steam at 120 °C in the absorber, which was able to drive a four-effect distiller to produce distilled water. For a single-effect and four-effect distiller, the COPs were 1.02 and 1.03, respectively, performance ratios (amount of distilled water to the amount of motive stem) were 2.19 and 5.72, respectively. They concluded that the four-effect distillation system combined with an OAHT was the most efficient.

### 2.3.2. Energy recover from industrial processes

Eisa et al. [92] analyzed the theoretical performance of an AHT assisting a distillation system. The authors concluded that a heat transformer could replace mechanical vapor compression by heat pumps in the distillation process with energy savings between 10% and 60%. Tufano [93] analyzed the performance of single and TSHT used to save energy in a distillation column and found that a steam saving factor as high as 0.4 could be obtained in distillation processes by the integration of AHT. Rivera et al. [94] reported the theoretical analysis of the use of SSHT and DAHT operating with the H₂O/LiBr mixture coupled to a butane and pentane distillation column in a Mexican refinery. The results showed that it was theoretically possible to reduce the energy consumed in the reboiler between 26 and 43% by the use of an SSHT at some specific conditions, and between 28 and 33% with a DAHT, for a wide range of operating conditions. Aly et al. [95] analyzed the application of AHT for energy conservation in the oleochemical industry. The heat transformer used 314 kW of vapor, which was condensed in a dump condenser and discharged. The analysis showed that the AHT could recover up to half of the energy achieving a GTL of 34 °C, producing steam at 3 bar which could be fully reused in the plant. The economic analysis showed that a payback period less than 18 months could be achieved based on a steam cost of 0.25$/GJ, an installed equipment cost of 535$/kW, an annual operation time of 7200 h, and a heat transformer efficiency of 0.45. Rivera et al. [96] proposed the design of a mobile pilot-plant for the production of environmentally clean steam. The unit consisted of an SSHT coupled to a mechanical vapor recompression system with a nominal output capacity of 260 kg/h of saturated steam at 3 bar absolute pressure for a liquid feed at a temperature of 80 °C and a COP of 0.48. Another application to produce steam by means of SSHT and DAHT using H₂O/LiBr was analyzed by Horuz and Kurt [97]. It was concluded that absorber temperatures as high as 130 °C and 160 °C with could be obtained with SSHT and DSHT, respectively, when heat was supplied to the evaporator and generator at temperatures of 90 °C. The maximum COPs were 0.482 and 0.377 with the SSHT and DAHT, respectively.

The same authors [98] analyzed a theoretical application of the AHT system in a textile company which produces hot water at 90 °C. The study considered to produce useful heat at 120 °C to be reused in the industrial process. It was shown that, by applying different modifications in the industrial process, the COP could be increased by 14.1%, the heat transfer at the absorber by 158.5% and the hot process water produced by 3.5% compared to the basic AHT system. Jeday et al. [99] evaluated an AHT utilizing waste heat from an industrial sulfuric acid plant. The system produced superheated steam at 180 °C from waste heat at 106 °C. A COP close to 0.45 was obtained. The authors concluded that from the economic point of view, the heat transformers are a good alternative to be used in industrial process to save energy. A detailed graphical exergy study based on the energy-utilization diagram was applied by Ishida and Ji [100] to humid air turbine cycle incorporated with a modified TSHT. Compared to a conventional AHT cycle, the overall cycle efficiency was increased by 2% and the specific work was increased by 7.3%. The exergy and exergetic-economic optimization of a cogeneration pulp and paper mill plant including the use of a DAHT was carried out by Cortés and Rivera [101]. Heat coming from the evaporator of the paper mill plant at temperatures between 70 °C and 80 °C was supplied to the DAHT to produce useful heat at temperatures between 90 °C and 120 °C to be supplied to the cogeneration plant and force plant boilers, saving about the 25% of the natural gas consumed by the plant. The improved CO₂ capture system with heat recovery based on the use of an AHT and a flash evaporator (FE) was analyzed by Zhang et al. [102]. Compared with the base CO₂ capture system of 3000 t/dCO₂ capture capacity from a 660MW coal-fired power unit, the AHT-FE-aided capture system reduced the heat consumption from 3.873 GJ/tCO₂ to 3.772 GJ/tCO₂.

![Schematic diagram of a heat transformer coupled to a solar pond.](Image)
and the corresponding energy saving was 26.2%. The economic analysis showed that the annual profit would be 2.94 million RMB. The payback period of the AHT-FE-aided capture system was approximately 2.4 years. Donnellan et al. [103] reported the economic evaluation of a TAHT in a small Irish oil refinery, examining various different natural gas price scenarios. The TAHT was capable of increasing the temperature of supplied heat by up to 140 °C with a COP of 0.14 corresponding to approximately 4.5 MW of energy saved. The results showed that at the present gas price, the capital cost of the (conventional) equipment was too high to make it financially attractive for the current industrial example, with an extremely high predicted payback period. However, a return to natural gas price levels observed in 2008 and 2009 would make the unit economically viable with a payback period of 5 years or less. Scott et al. [104] investigated the technical and economic feasibility of incorporating an absorption heat transformer to increase the energy efficiency of an evaporation-crystallization plant in a sugar mill, having an intake capacity of 17.5 kton of sugar beets per day. The authors proposed the use of an open multi-compartment AHT for different steam temperatures. The results of the simulations revealed that the total amount of live steam used in the evaporation plant could be reduced by 11.8–16.4%, depending on the temperature level allowable in the crystallization plant. The authors reported that the payback period of this type of investment varied from 1.8 to 4.7 depending of the energy cost and with an annual operation time of 8000 h/year.

2.3.3. Other applications

In addition to the heat transformer applications previously described, AHT have been proposed for other uses such as to increase the temperature of the useful heat produced by solar ponds as it is shown in Fig. 8. In regard to this, a thermodynamic study of an AHT coupled to a solar pond was reported by Murugesan et al. [105]. The heat transformer used R134a as refrigerant and organic fluids DMAC and DMETEG as absorbents. The results showed that, for a high temperature lift, R134a/DMAC had superior performance compared to R134a/DMEETEG. For both mixtures the COP varied from 0.1 to 0.34, while the GTL varied from 10 °C to 30 °C. Mathematical models of SSHT and AAHT operating with the H₂O/LiBr and H₂O/Carrol mixtures were developed by Rivera et al. [106] to simulate the performance of these systems coupled to a solar pond. The results showed that the SSHT and DAHT were the most promising configuration to be coupled to solar ponds. With SSHT it was possible to increase solar pond’s temperature up to 50 °C with COPs of about 0.48, and with DAHT up to 100 °C with COP 0.33. Sözen [107] developed a mathematical model for that purpose and found that the maximum upgrading of solar pond’s temperature by the heat transformer was obtained at 51.5 °C and gross temperature lift at 93.5 °C with COP of about 0.4. The maximum temperature of the useful heat produced by the AHT was approximately 150 °C. Şencan et al. [108] proposed the use of an SSHT operating with aqueous ternary hydroxide fluid to upgrade the heat deliver by a solar pond. According to the authors COP close to 0.5 and GTL up to 70 °C could be achieved.

2.3.4. Conclusions of heat transformers applications

From the bibliographic review of this section, it was found that there are several theoretical studies based on the first and second laws of thermodynamics regarding the use of heat transformers for water purification. These studies cover the use of SSHT as well as DAHT, TSHT, and OAHT all of them operating with an H₂O/LiBr mixture and obtaining, depending on the heat transformer used, COPs between 0.25 and 0.5. According to Romero and Rodriguez [81] it is possible to produce distilled water when heat is supplied to a heat transformer at temperatures starting at 65 °C. Srinivas et al. [86] published the only study that did not use H₂O/LiBr; they propose a multiple effect desalination system integrated to an SSHT operating with an H₂O/(LiCl + LiNO₃) mixture, with a highest COP of about 0.5 and with energy consumption between 128 and 124 kWh/m³ to produce 1 m³/h of distilled water.

With respect to energy recovery in industrial processes, several theoretical studies have been conducted regarding the use of one-stage or advanced heat transformers in industries such as: distillation, sugar mill, textile, chemical, oleochemical, and in a cogeneration of pulp and paper mill plants. Depending on the application and the type of transformer used, the energy saving in the different industries varied between 10% and 60%. The payback periods in an evaporation-crystallization plant in a sugar mill varied from 1.8 to 4.7 years [104], in oleochemical industries less than 18 months [95], in a coal-fired power industry approximately 2.4 years [102], and in an oil refinery less than 5 years at the natural gas price levels observed in 2008 and 2009 [103].

Other applications have exclusively focused in theoretical studies for the use of single-stage or advanced AHT systems to raise the temperature of solar ponds. According to Rivera et al. [106] using the H₂O/Carrol mixture with SSHT, it was possible to increase the solar pond’s temperature up to 50 °C with COPs of about 0.48.
0.48, and DAHTs of up to 100 °C with COPs of 0.33. Using a water/ternary hydroxides mixture with a SSHT [108] the temperature increased up to 70 °C with a COP of 0.5.

Fig. 9 shows the coefficients of performance against gross temperature lifts for the diverse industrial processes analyzed.

3. Experimental studies

The following section presents everything in reference to experimental studies regarding heat transformers including the description and research of the main cycles, either single-effect or advanced, as well as the use of conventional and alternative mixtures and their possible applications.

3.1. Single stage heat transformers

3.1.1. SSHT operating with water/lithium bromide

Energy and exergy analysis of an experimental SSHT of 500 W capacity operating with the H2O/LiBr mixture were carried out by Rivera et al. [109]. The GTLs varied from 22 °C to 27.5 °C, and the highest COP of 0.45 was achieved at the highest solution concentration of 59%. It was observed that in general the absorber accounted with more than half of the total irreversibility in the system. In order to reduce the irreversibility reported by Rivera et al. [109], Colorado et al. [110] developed a model based on direct and inverse artificial neural networks. It was shown that by using the proposed methodology the total irreversibility could be reduced up to 14%. An experimental study was performed by Olarte-Cortés et al. [111] on a graphite disk absorber coupled to an AHT operating with H2O/LiBr. According to the authors, the graphite was used in order to eliminate the corrosion problems in the absorber. The authors reported that the heat transfer coefficient varied from 0.62 to 1.53 kW/m² K. The heat transfer coefficients were similar than those reported by Kim et al. [112] utilizing a vertical absorber of concentric tubes made of stainless steel, but lower than those reported by Deng and Ma [113] using an absorber of horizontal tubes made of cooper, both operating with the same mixture. The analysis of effective wetting area of a horizontal generator for an absorption heat transformer operating with H2O/LiBr was carried out by Lazcano-Vélez et al. [114]. They analyzed the wetting area and falling film behavior of the mixture on a bank of sixteen horizontal tubes. The results showed the distribution of absorbent mixture, along the tubes of the bank at different mass flow rates per unit length (0.006–0.034 kg/m s). The most regular film distribution of the mixture, through the tubes of the bank, was obtained with the flow of 0.025 kg/m s, which gave the best results of heat transfer efficiency, with values between 80 and 98%. Ma et al. [115] studied the heat transfer and thermodynamic performance of a H2O/LiBr AHT with vapor absorption inside vertical spiral tubes. The available COP in the experiments was higher than 0.4. The heat and mass transfer coefficients of the absorber increased with the increase of the flow rate of LiBr solution, up to 400 W/m² K and 0.013 kg/m²s at waste heat temperature of 90 °C.

In order to improve the performance of the systems operating with the H2O/LiBr mixture, some studies have been carried out on the use of additives, Rivera and Cerezo [116,117] reported the results of an experimental study of the use of 1-oktanol and 2-ethyl-1-hexanol as additives in the performance of an SSHT operating with H2O/LiBr. It was concluded that the 1-oktanol additive increases slightly the absorber temperature and the COP; however, the 2-ethyl-1-hexanol increases considerably the performance of the system. Absorber temperatures up to 7 °C higher and COP up to 40% higher were obtained by using this additive than those obtained without additive.

3.1.2. SSHT operating with alternative mixtures

As it was mentioned in Section 2.1.3, currently the H2O/LiBr has been the most used mixture in AHT but it has some major disadvantages, reason why different mixtures have been proposed or used. Rivera et al. [118] developed a SSHT of 500 W capacity operating with the H2O/Carrol mixture (see Fig. 10). The COPs were in the range 0.1–0.2 while the highest GTL was 52 °C. The authors commented that COP values were low because of the low capacity of the facility and the high of the heat losses. Rivera et al. [119] compared the performance of a SSHT operating with H2O/LiBr and the H2O/Carrol mixtures. For both mixtures the COP varied between 0.3 and 0.4, however, the GTL values were higher for the system operating with the H2O/Carrol than those obtained with H2O/LiBr. The highest GTL with H2O/LiBr was 43 °C, while with the H2O/Carrol the highest GTL was 52 °C. The authors considered that because the H2O/Carrol mixture has higher solubility than H2O/LiBr and high GTL, the alternative mixture seemed to be a better alternative mixture to be used in AHT. Similar conclusions were reported by Silva-Sotelo and Romero [120] comparing the same mixtures in a TSHT. Ibara-Bahena [121] reported the experimental evaluation of a SSHT built with commercial plate heat exchangers operating with the H2O/Carrol mixture. The heat powers were measured from 1.32 to 1.35 kW for the generator, 0.97–1.33 kW for the condenser, 0.99–1.35 kW for the evaporator and 0.69–0.81 kW for the absorber. The experimental GTLs varied from 18.5 to 22.2 °C, while the COPs varied from 0.30 to 0.35. Ibarra-Bahena et al. [122] analyzed the effectiveness of a plate heat exchanger used as an economizer integrated into an experimental SSHT operating with the H2O/Carrol mixture. The economizer effectiveness ranged from 0.69 to 0.71. The results showed that at low absorber temperatures, the COPs were almost the same for different economizer effectiveness, however, at absorber temperatures higher than 135 °C the COPs, with economizer effectiveness of 0.7 and 0.9, were almost twice than those obtained without the economizer. Pataskar et al. [123] carried out an experimental evaluation of a small AHT operating with H2O/LiBr, H2O/LiBr + LiCl (1:1 by weight), and H2O/LiCl. It was demonstrated that under the same operating conditions the maximum COP for the H2O/LiBr mixture was 0.26, for the H2O/LiBr + LiCl was 0.31 and for the H2O/LiCl the COP was 0.38. Bokelmann and Steimle [124] presented a report on an experimental research to discover new working fluids for sorption plants. Some of the most important results for heat transformer applications were presented in the form of graphs or tables and the suitability of the new working fluids was compared with some well-known working couples. The mixtures analyzed were TFE-Chi, TFE-DTG, TFE-EP, TFE-ICh, TFE-MP, TFE-NMP, TFE-Pyr, TFE-TEG, HFIP-NMP and PFPA-DTG. The authors found that the mixtures TFE-NMP and TFE-Pyr were specially promising in spite of the higher cost and lower heat transfer coefficients when compared with traditional mixtures. George and Srinivasra [125] evaluated an SSHT of 3 kW heating capacity operating with R21/DMF. Heat source temperature and condensing temperature were varied in the ranges 50–70 °C and 20–40 °C, respectively. Heat delivery temperatures up to 85 °C and temperature lifts up to 20 °C were achieved. The COP ranged from 0.2 to 0.35, whereas exergetic efficiencies between of 0.3 and 0.4 were obtained. Barragan et al. [126] reported the experimental results of the performance of a SSHT operating with the H2O/LiCl mixture. The results showed that GTLs higher than 30 °C could be obtained with a COP of 0.45. The same authors [127] reported experimental results with the binary mixtures H2O/CaCl2 [128], H2O/MgCl2 and with the ternary mixtures H2O/LiCl + ZnCl2 and H2O/CaCl2 + ZnCl2 [129]. With the H2O/CaCl2 the highest GTL was 19 °C and the COP was 0.45, while with the H2O/CaCl2 the highest GTL was 0.18 and the COP was 0.273. Regarding to the ternary mixtures, the H2O/LiCl + ZnCl2 solution
showed in general better performance than the H₂O/CaCl₂ + ZnCl₂ mixture. The highest GTL obtained with the former solution was 37.5, while the COP was 0.28. Stephan et al. [130] built a pilot plant and developed a model to simulate the dynamics of a heat transformer working with the mixture H₂O/NaOH. The results showed that COPs as high as 0.49 could be obtained. Xiao et al. [131] carried out a vapor–liquid equilibrium study of an absorption heat transformer working with HFC-32/DMF. The authors reported that according to its thermodynamic properties the mixture could be an alternative be used in AHT but they did not report its use. The solubility of R134a in DMEDEG and DMETrEG was measured by Zehioua et al. [132] using the “static-analytic” method at temperatures between (303 and 353) K. The study remarked the possibility of the use of those mixtures as working fluids in AHT.

3.1.3. Conclusions of SSHT

Experimental studies of SSHT operating with the H₂O/LiBr mixture have been carried out from the point of view of the first and second law of thermodynamics [109], the development of new components [111–115], and the use of additives in order to improve the performance of the system. Regarding the latter ones it was found that using 2-ethyl-1-hexanol considerably increases the performance of the system, since absorber temperatures up to 7 °C higher and COPs up to 40% higher were obtained by using this additive compared to those obtained without additive [116,117].

Regarding the study of new mixtures, from the many thermodynamically analyzed, it was reported that the TFE/NMP, TFE/Pyr, and HFC-32/DMF were specially promising compared to traditional mixtures; however, there are no reports of the operation of heat transformers using these mixtures [124]. There is a report of the use of other mixtures like H₂O/CaCl₂ [128], H₂O/MgCl₂ and H₂O/LiCl/ + ZnCl₂ [129], and R21/DMF [125], but the results are not compared with the H₂O/BrLi mixture and from their analysis it is not clear if they represent and advantage over its use. Of all the mixtures analyzed, the only ones obtaining better results when compared to the H₂O/LiBr mixture under the same operating conditions were the H₂O/Carrol, H₂O/LiBr + LiCl, and H₂O/LiCl mixtures. It was reported that an AHT operating with H₂O/LiCl achieved COPs up to 31% higher than those obtained with the H₂O/BrLi mixture [123], and although with the H₂O/Carrol mixture the COPs were similar to...
those obtained with the H$_2$O/LiBr mixture, the GTLs were up to 7 °C higher [118].

3.2. Advanced absorption heat transformers

In regards to experimental studies of AAHT, a novel multi-compartment AHT for different steam temperatures was proposed by Scott et al. [133]. Both the absorber and generator were partitioned in a number of compartments according with the steam temperature levels. The authors reported values of the experimental heat transfer coefficients for the but the authors did not report values of the COP. Silva-Sotoelo et al. [134] and Romero et al. [135] reported the results of a TSHT built with compact heat exchangers of 1 kW capacity controlled by flow ratio operating with the H$_2$O/Carb mixture (see Fig. 11). The waste heat energy was added at the system at 70 °C achieving 128 °C in the second absorber with a COP of 0.326. Eriksson and Jernqvist [136] reported the preliminary results of a heat transformer with self-circulation operating with the mixture H$_2$O/NaOH. The self-circulation was reached according to the thermosiphon principle. The pressure difference in the apparatus was achieved through a difference in hydrostatic pressures. The COPs achieved were around 0.26 when the heat was supplied to the generator at 83 °C, to the evaporator at 107 °C and the useful heat produced in the absorber at 125 °C. Alonso et al. [137] carried out an experimental study of an innovative AHT using partially miscible working mixtures. The system operated with the n-heptane/DMF mixture. Gross temperature lifts of 8 °C were achieved with COPs between 0.3 and 0.4 (see Fig. 12). An experimental study of an innovative absorption-demixing heat transformer (ADHT) operating n-heptane/DMF and cyclohexane/DMSO was carried out by Alonso et al. [138]. The system base its performance in the use of partially miscible working mixtures. Gross temperature lifts as high as 50 °C were obtained with COP between 0.27 and 0.42.

3.2.1. Conclusions of AAHT

The experimental works seen in this section regarding the study of advanced heat transformers are few when compared to the works reported on single-stage heat transformers. The studies have basically focused on multi-compartment heat transformers [133], two-stage [134,135], self-circulation [136], using partially miscible working mixtures [137], and absorption demixing [138]. Due to big differences among them in terms of their configuration, fluids used, and scarcity of reported data, a comparison among them to determine the best one, is not possible. In all the cases the COPs varied between 0.2 and 0.42.

3.3. Applications

3.3.1. Small scale application

In regards to absorption heat transformer applications. First and second law of thermodynamics were used by Rivera et al. [139] to analyze the performance of an experimental AHT used for water purification of 700 W capacity operating with the H$_2$O/LiBr mixture built mainly in stainless steel. The heat was supplied to the generator and evaporator at about 80 °C, and the heat was delivered from the absorber to the water purification system at about 100 °C. The COPs varied between 0.23 and 0.33, while de ECOPs varied from 0.15 to 0.24, and the water purification between 400 and 800 mL/h. Huicochea et al. [140] presented the results of the experimental tests applied to a portable water purification system integrated to an AHT of about 1 kW of capacity operating with the H$_2$O/LiBr mixture. The heat transformer operated with waste heat temperatures from 68 °C to 78 °C achieving COP values between 0.1 and 0.3, and the distilled water quality varied between 200 and 500 mL/h. Huicochea and Siqueiros [141,142] reported the results of an SSHT of about 700 W capacity using the H$_2$O/LiBr mixture (see Fig. 13). The authors reported that typical COP values could by increased by means of heat recycling from the water purification system to the AHT. The maximum COP was 0.432, obtaining a maximum of 684 mL/h of distilled water for a generation and evaporation temperatures around 110 °C. With the previous results, Hernández et al. [143] developed a model based on artificial neural networks to determine on-line the optimum system operating conditions. The error propagation on COP was reported by Colorado et al. [144]. Hernández and Colorado [145] determined the uncertainty of the COP for the same system, and Escobar et al. [146] carried out online COP estimations in order to analyze and modify in real time the system operating conditions. An AHT working with H$_2$O/LiBr solution, coupled with a seawater distillation system was evaluated by Sekar and Saravanan [147] (see Fig. 14). The heat was supplied to the generator and evaporator between 60 °C and 80 °C. The heat input to the generator was fixed to 5 kW. The results showed that the COPs varied between 0.3 and 0.38 obtaining a maximum distillate flow rate of 4.1 kg/h. The analysis of the behavior of an

Fig. 14. Photograph of the experimental set up of the absorption heat transformer coupled distillation system developed by Sekar and Saravanan [147].

Fig. 15. Photograph of the experimental heat transformer for water purification developed by Meza et al. [150].
experimental absorption heat transformer for water purification for different mass flux rates in the generator was carried out by Huicochea et al. [141,148]. The results showed that the system irreversibilities increased, while the COP and the ECOP decreased with an increment of the mass flow of hot water supplied to the generator. Also, it was shown that the system performance improved when the production of purified water increased due to the increment of the heat recycled to the generator and evaporator. The COP varied from 0.16 to 0.26. Huicochea et al. [149] studied the potential of a novel cogeneration system consisting of a 5 kW proton exchange membrane fuel cell (PEMFC) and an AHT. The dissipation heat resulting from the operation of the PEMFC was used to feed the AHT, which was integrated to a water purification system. Therefore, the proposed system would produce electricity, heat and distilled water. The results showed that experimental values of COP of the AHT and the overall cogeneration efficiency achieved values of 0.256 and 0.571, respectively. An experimental study of an AHT operating with H2O/LiBr for water purification with single-effect evaporation was carried out by Meza et al. [150] (see Fig. 15). The maximum heat recovered from the distillation process was of 541 W with a flow of distilled water of 888 mL/h and a COP of 0.391, reaching a useful heat of 1157 W.

Gomez-Arias et al. [151] reported a study for steam generation using a H2O/Carrol SSHT. The experimental evaluation was carried out with plate heat exchangers acting as generator in horizontal and vertical position. The results showed that the heat exchangers in vertical positions were better than horizontal positions since the evaporation take place at lower length of the heat exchanger. The authors did not report the COP of the system. A new concept of a closed drying system with superheated steam provided from an AHT was proposed by Nomura and Nobuya [152]. The heat transformer was driven directly by heat from a solar collector. It was concluded that the system would be useful for industries where high temperature drying (over 100 °C) is required. A TSHT of about 1 kW of capacity was designed and constructed by Currie and Pritchard [153] to investigate the potential for dehumidifying and reheating a simulated dryer exhaust stream to make it suitable for recycling to the dryer inlet. The performance data for the heat transformer indicated that an airstream could be reheated to a temperature of 160 °C, using a lithium bromide solution of 68% w/w, with a circulation ratio (LiBr: steam flow) of 14.8 with a COP close to 0.2. Temperature lifts between 50 and 70 °C were possible in the reheat column when using a low circulation ratio and a high LiBr concentration. The results of a 10 kW experimental AHT operating with H2O/NaOH with self-circulation (obtained according to the thermosiphon principle), installed on a pulp and paper mill were reported by Abrahamsson et al. [154]. The heat transformer used steam at 100 °C in both the generator and evaporator and the absorber produced steam at 123 °C. The authors did not reported the COP but they estimated that was very low due to the high heat losses and the low capacity of the facility. Rivera [155] carried out an experimental evaluation of a single-stage heat transformer of 1 kW of capacity operating with the H2O/Carrol mixture to demonstrate the feasibility of these systems to increase the temperature of the heat obtained from the solar ponds. GTLs as high as 50 °C were obtained and the maximum temperature of the useful heat produced by the heat transformer was 132 °C. The COPs for the unit were in the range 0.14–0.36.

3.3.2. Industrial applications

Abrahamsson et al. [154] reported the results of a heat transformer plant, delivering 100 kW, designed and installed in a major pulp and paper mill in Swedish. The unit was directly incorporated with one of the evaporation plants of the mill. The AHT was designed to be operated with vapor supply at a temperature range of 87–100 °C and to produce steam at a temperature range of 110–135 °C with the working pair H2O/NaOH. Because of the plant was still in the first test period the authors did not report the COP, but they performed an economic evaluation to determine the economic feasibility of incorporating an AHT in this type of evaporation plant. They found that assuming an installation cost of the AHT of 410 $ kW⁻¹ and considering a COP of 0.45 the payback period was 3.1 years. Mostofizadeh and Kulick [156] developed a pilot plant of 100 kW and then built a 4 MW heat transformer plant denominated TRAXX (currently known as double absorption) operating with the H2O/LiBr mixture to recover heat from an industrial process. The pilot plant of 100 kW was used as a prototype to produce clean steam upgrading the heat from 80 °C to 121 °C with and average COP of 0.52. The 4 MW plant was fed with steam from a counterpressure turbine at 80 °C, and the useful heat produced was given up into the steam distribution system at about 141 °C achieving a GTL around 60 °C. The experimental COP was not reported for this plant but the authors estimated that considering a COP around 0.45 the payback period of the heat transformer would be 2.4 years. Ma et al. [157] reported the test results of the first industrial-scale absorption heat transformer equipment in China, to recover the waste heat released from mixture of steam and organic vapor at 98 °C in the coacervation section, of a synthetic rubber plant of Yanshan Petrochemical Corporation, Beijing, China (see fig. 16). The recovered heat was used to heat hot water from 95 to 110 °C, feeding it back to the coagulator as the supplementary heating source. The AHT system operated with the H2O/LiBr mixture with a power capacity of 5000 kW. The results showed that the mean COP was 0.47, the gross temperature lift of 25 °C and the payback period was 2 years.

3.3.3. Conclusions of applications

As seen in the “Small scale applications of AHT” section, most of the applications have centered either in water purification or in vapor production. In regards to water purification, several prototypes have been developed with capacities that vary from 700 W to 5000 W and with COPs that vary between 0.15 and 0.43, and

![Fig. 16. Photograph of the industrial-scale absorption heat transformer developed by Ma et al. [157].](image-url)
purified water capacities that varied between 0.6 and 1.6 kg/h for each kW of power supplied to the heat transformer. Since the prototypes were small, none of the cases reported payback periods. Another one of the main applications of heat transformers is in vapor production. In these cases, due to the small capacity of the prototypes, variations in the capacities were between 1 kW and 10 kW of exit power. The different authors reported COPs between 0.1 and 0.2, but concluded that at higher power, the COPs could increase their values close to 0.4.

There are few works reported in the literature in relation to industrial applications regarding the use of heat transformers. When mentioned, they have been used in vapor production, in the pulp and paper industry, and in the petrochemical industry. The COPs have varied between 0.45 and 0.47 and the payback periods between 2 and 3.1 years.

Regarding the payback periods, it is important to mention that in the articles published by Aly et al. [95] in 1993, Abrahamsson et al. [154] in 1995, and Scott et al. [66] in 1999 when the price of natural gas was similar to the current one (varying between 2.3 and 3.0 dollars per Mbtu), the payback periods were lower than 18 months, 3.1 years, and between 1.8 and 4.7 years, respectively, which were very attractive. In the study conducted by Ma et al. [157] in 2003, the price of natural gas was above 5 dollars with a payback period of 2 years, and comparing it to the current price will make it less than four years. In 2014 Donellen et al. [103] published an article stating that if the prices of natural gas were the same as they were in 2008 (between 9 and 11 dollars), the payback period of the installation of a heat transformer would be less than 5 years.

From the above mentioned, it becomes clear that even with the decrease in fuel prices in the last months, the use of heat transformers in industrial processes for the recovery of energy is still appealing.

Moreover, it is worth mentioning that energy saving is important not only from an economic, but also from an environmental point of view, since energy saving also implies a reduction in CO₂ emissions, one of the main causes of global warming and all its consequences. All of the above makes us believe that heat transformers will have an even bigger impact in the near future.

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References


