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Operational improvements to increase the efficiency of an absorption heat pump connected to a multi-effect distillation unit

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HIGHLIGHTS

- Experimental evaluation of a DEAHP performance connected to a MED unit.
- Identification of operational problems in a LiBr double effect heat pump.
- Results show increase in the COP, more stable behavior and faster start-up stage.

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ABSTRACT

The performance of a double-effect LiBr–H_2O absorption heat pump connected to a solar multi-effect desalination plant has been analyzed experimentally. A detailed study of the main operation problems has been carried out in a first experimental campaign with the aim of identifying new control strategies to improve the behavior of the system at stationary nominal conditions, as well as to increase its thermal efficiency. An improved control strategy is proposed to deal with the identified problems and has been validated in a second experimental campaign. Results of these experiments have shown an improvement of the heat pump performance when the refrigerant flows continuously between the low-temperature generator and the condenser. By avoiding intermittent water flow, it is easier to keep LiBr solution levels in both generators constant, gas consumption is lower, it takes less time to reach steady state and a higher average coefficient of performance is reached.

1. Introduction

The efficiency of a Multi-Effect Distillation (MED) process can be enhanced by recovering part of the thermal energy rejected in the distillation process [1]. This can be done by means of an absorption heat pump or a vapor compression (VC) system, which may be either thermal (TVC) or mechanical (MVC) [2]. Connecting an Absorption Heat Pump (AHP) to a MED unit is the most efficient option, and has been deemed as one of the few which make the thermal desalination processes competitive with reverse osmosis [3]. The potential to increase the performance ratio of single-effect evaporation desalination systems with a heat pump has been shown by several authors [4,5]. Also, there are several research works studying the potential of the combination of AHPs with MED systems. Aly [6] proposed a novel configuration consisting of a single-effect water/lithium bromide (LiBr–H_2O) AHP and a 20-effect MES (multi-effect stack) with a new record low temperature level down to 6 °C, which replaces the condenser and evaporator of the heat pump. The system is able to produce around 6000 m^3/day of fresh water at a performance ratio (kg of distillate for every 2326 kJ of thermal energy supplied to the distillation unit) of 14.2. Su et al. [7] studied a system composed of a LiBr–H_2O double-effect absorption heat pump (DEAHP) and a 9-effect low-temperature MED (LT-MED), obtaining a performance ratio (PR) of 17.15, much higher than that of an MED plant using steam ejectors (i.e. 11.05). Wang and Lior [8] carried out a thermal performance analysis of a LT-MED coupled with a single-effect LiBr–H_2O AHP, showing a 60–78% water production increase over a stand-alone LT-MED unit powered by the same heat source. Moreover, heat pumps have shown their potential in poly-generation systems by the combination of absorption refrigeration

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heat pumps and MED systems. Wang and Lior [9,10] presented a performance analysis of a combined refrigeration and water system which consisted in the integration of a $LiBr-H_2O$ refrigeration unit, a $LiBr-H_2O$ heat pump and a LT-MED, and obtained an energy saving rate of 42% compared with the individual systems.

The feasibility of coupling an AHP with an MED plant has been proven at the solar test facilities of Plataforma Solar de Almería (PSA) in Spain. During the nineties, a first prototype of a Double Effect Absorption ($LiBr-H_2O$) Heat Pump (DEAHP) manufactured by the French company ENTROPIE was installed and connected to a 14-effect MED plant, improving the overall heat consumption of the system [11,12]. Based on this previous background and experience, a new experimental facility was erected in 2001 under the European AQUASOL Project (Enhanced Zero Discharge Seawater Desalination using hybrid solar technology, Contract no. EVK1-CT2001-00102). In this research and demonstration project a second DEAHP prototype, also manufactured by ENTROPIE, was connected to the MED plant at the PSA. In the previous prototype, the low-temperature condenser was directly the first effect of the MED unit. In the new one, a closed water circuit extracts the heat from the absorption heat pump and delivers it to the first cell of the MED unit. Alarcón-Padilla et al. [13,14] evaluated the connection of the second DEAHP prototype to the MED unit and the thermal efficiency of the combined system. The performance ratio of the MED plant connected to the DEAHP was 20, while for the MED plant operating alone the performance ratio was 10 [13]. Other conclusions were that the prototype was reliable during continuous operation but took a long time to reach steady state. Also, after assessing different configurations for the connection of the DEAHP to the MED unit one of the main conclusions was that the best option for connecting the heat pump and the distillation unit was indirect connection by means of two auxiliary water tanks [14].

The coupling of an AHP and a solar MED plant such as that of the PSA imposes some problems which affect the performance of the system. On one hand, the reliability exhibited by the system has still significant improvement opportunities. In addition, although the tests have been done so far with a gas burner as the high temperature heat supply of the DEAHP, the configuration is devised to be fully solar by making use of the increasing availability of small parabolic trough solar collectors designed for process heat. The testing of the performance of heat pumps driven either by only solar energy or by hybrid gas/solar has been published in the literature [15–17] showing its environmental benefits when compared to the conventional systems and making them more attractive in economic grounds. As a matter of fact, it is the aim of the Plataforma Solar de Almería-CIEMAT to connect the existing DEAHP to a new solar field based on parabolic trough solar collectors operating at about 200 °C. Due to the variability of the energy source and the intermittent operation, the improvement of the system control for future operation out of nominal conditions is of major interest. Also, as is the case of all solar energy applications, improving the performance allows for a reduction of the investment costs by reducing the size of the solar field.

Most of the studies of heat pumps have been devoted to increase the coefficient of performance (COP) by modifications in the absorption heat pump cycles [18], like White and O'Neill [19] who included a liquid-phase separation step and an additional distillation step in the cycle for the separation of the working fluid from the absorbent. In this modified cycle, the absorbent was recovered from the weak solution by distillation and the liquid-phase separation step was used to recover additional volatile working-fluid from the liquid existing in the evaporator. A computer model was developed to simulate the performance of the cycle using cyclohexane and aniline as working fluids and significant improvements in the cycle performance were achieved. However, it was found difficulty to achieve the optimal performance due to the fact that the liquid exiting in the evaporator is too rich in the volatile component to achieve liquid-phase separation. Yan et al. [20] proposed a novel high-efficient absorption refrigeration cycle in which water/lithium bromide is used as working pair. It is an improved single-effect/double-lift configuration that consists of high temperature generator, low temperature generator, solution heat exchangers, evaporator/absorber, heat regenerator, vapor–liquid separator, high-pressure absorber, low-pressure absorber, solution pumps, evaporator and condenser. Comparing to the single-effect cycle, it was proved that in this cycle the refrigerant liquid condensed is subcooled through the vapor–liquid separator before flowing into the evaporator so that more cooling capacity per unit mass of refrigerant can be obtained. Also, it was concluded that much lower temperature of the discharged waste gas/water was obtained in this cycle due to the greater concentration differences between the strong and the weak solution in the low temperature generator. From the simulations, it was found a temperature of 20 °C lower than that of the single-effect cycle. It is important to highlight that this new cycle reduces the irreversible loss of refrigerant during the throttle process and improves the efficiency of the cycle from a thermodynamic point of view. Likewise, it can operate under a larger available temperature range of heat sources than the single-effect cycle. Other authors have studied the variation of the design parameters to increase the performance of the heat pump. Xu and Dai [21], and Arun et al. [22] studied the effect of the solution circulation ratio on the COP for a double-effect series and parallel flow, respectively, showing that the COP increases as the solution circulation ratio decreases. Others have opted for including technological improvements to increase the energy efficiency of the heat pumps [23], such as: (i) the incorporation of a heat-driven ejector to the heat pump [24,25]. Sarkar [24] carried out optimization studies along with optimum parameters correlations, for ejector-expansion transcritical CO_2 heat pump cycle and found that efficiency can be improved by maximum 9% by using ejector, concluding that the ejector may be the best alternative expansion device for low-capacity transcritical CO_2 heat pump systems. On the other hand, Wongwises and Disawas [25] presented experimental data of the system performance of a two-phase ejector refrigeration cycle and they were compared with a conventional one, showing that the former gives a higher cooling capacity lower compressor pressure ratio, lower discharge temperature and a higher coefficient of performance than the latter one; and (ii) the change of the working fluid [26–28]. Niang et al. [26] used a partially miscible mixture as working fluid in an absorption/demixtion heat pump, resulting in an increase in the COP between 5 and 10 times higher. Jian et al. [27] carried out the performance calculation of a single effect absorption heat pump using $LiBr + LiNO_3 + H_2O$ as a new working fluid, and it was compared with the use of $LiBr + H_2O$. It was proved that this proposed working fluid increased the COP by about 5% than using $LiBr + H_2O$ as working fluid. It was also found lower crystallization temperature, and less corrosivity. Wu et al. [28] presented a comparison of the performance of an absorption heat pump at different generating temperatures, evaporating temperatures and condensing temperatures, using $NH_3 + H_2O$, $NH_3 + LiNO_3$ and $NH_3 + NaSCN$ as working fluids. From the study, they concluded that $NH_3 + LiNO_3$ requires lower generating temperature, lower evaporating temperature and higher condensing temperature than other solutions for the same heat pump cycle. Only a few studies are focused on the operation optimization in order to improve the COP, like Guo et al. [29] who investigated an experimental set-up of air-source heat pump water heater system by developing a simulation model from which operational parameters like the optimal start-up