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Sorption-based desalination systems: A comparison

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Abstract

This study compares the performance of absorption and adsorption desalination systems reported in the literature. A performance metric is defined based on the second-law analysis and is used in the present comparison. It has been observed that absorption desalination systems based on heat-pump cycle offer superior efficiency compared to adsorption systems.

1. Introduction

The persistent quest to meet the ever-increasing potable water demand in the world has urged researchers to look for new efficient and sustainable solutions to extract freshwater by seawater desalination. Commercial desalination technologies can be classified into two major categories: (i) membrane-based processes; and (ii) thermally-driven systems. Despite Reverse-Osmosis (RO) being the most deployed technology, with 59% global share, the drawbacks of this efficient technology include the need for high-grade power (electricity) for operation -which usually comes from fossil fuels thus not sustainable- as well as high maintenance requirements [1]. On the other hand, conventional thermally-driven units have their drawbacks. For example, multi-stage-flashing (MSF) demands a relative high driving temperature source for operation, as much as 120 °C, and are known for their high energy consumption and tendency for scale formation and corrosion [2], [3]. Furthermore, multi-effect-desalination (MED) units are difficult to scale down for small-size applications due to the complexity and the large number of parts associated with their design [4].

Adsorption desalination (ADD) is developed using sorption cooling cycles with the aim of overcoming the above-mentioned disadvantages of conventional desalination methods. ADD cycles utilize solid sorbent to produce freshwater and cooling effect. The units built based on this concept could use low-grade thermal energy (temperature below 90 °C) from waste-heat and non-concentrating solar collectors [3], [5] and do not have major moving parts. The evaporator works at low-temperatures (< 35 °C) which means the problem associated with corrosion and fouling may be mitigated or eliminated [3]. ADD can also be designed to provide cooling as a by-product, which is a desirable feature for application in hot and dry regions like the Middle East and North Africa (MENA). These advantages, in addition to low noise operation and flexibility in energy source without limitation on the upper operating temperature range, make ADD of great interest for decentralized freshwater production and air conditioning, where saline water is available. The majority of ADD systems considered in the literature are based on adsorption heat pump (ADHP) cycle.

Absorption desalination (ABD) is another option to utilize liquid-sorbents for freshwater and cooling co-generation. The cycle can be an open-cycle as in an ADD, or a closed-cycle in which the heat generated from the condenser/absorber of a absorption heat pump (ABHP) or a heat transformer (ABHT) is used to evaporate saline water for potable water production [6]. The aim of this study is to compare the performance of ADD and ABD systems presented in the open literature.

2. Methodology

The most commonly used metric in evaluating the performance of desalination units is the performance ratio (PR), which is defined as:

$$\text{Performance ratio (PR)} = \frac{\dot{m}_{distillate}}{\left[\dot{Q}_{in}/h_{fg}\right]} \qquad (1)$$

where, $\dot{Q}_{in}$ (kW) is the rate of energy input, and h_{fg} (kJ/kg) is the latent heat of evaporation. This definition is based on the first-law of thermodynamic analysis and does not account for the quality of the energy provided to the system. It is useful either to compare systems utilizing the same energy source, or to benchmark improvement in the performance of a specific system. Therefore, another performance metric is defined in this study based on the second-law of thermodynamics and is used to provide a more comprehensive comparison for the systems under study working at different operating temperatures.

According to the second law of thermodynamics, there is a minimum work needed for separating the impurities from water physically. This minimum specific work $w_{\min}$ is approximately 0.74 kWh/m^3 for water with 35,000 mg/L impurities [7]. If this least work is assumed to be supplied by an ideal engine with efficiency η_{ideal}, then the minimum specific heat input (in kJ/kg) is given by:

$$q_{\min} = \frac{w_{\min}}{\eta_{ideal}} = \frac{w_{\min}}{\left[1 - \dfrac{T_0}{T_{source}}\right]} \tag{2}$$

where, T_{source} and T_0 are the temperatures (in Kelvin) of the source and environment, respectively. Accordingly, a modified performance ratio (MPR) is defined in this study as:

$$\text{Modified performance ratio (MPR)} = \frac{\dot{m}_{distillate}}{\left[\dot{Q}_{in}/q_{\min}\right]} \times 100\% \tag{3}$$

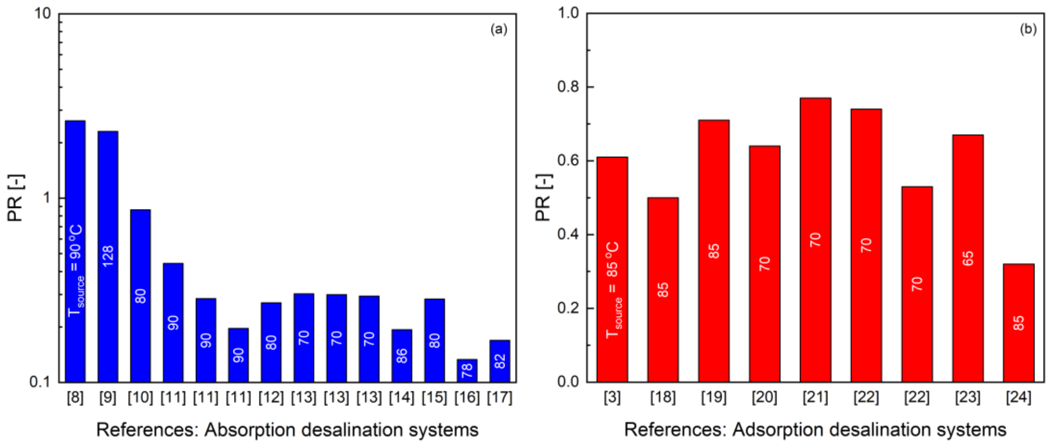

Fig. 1: (a) Absorption [8]–[17], and (b) adsorption [3], [18]–[24] desalination systems presented in the literature.

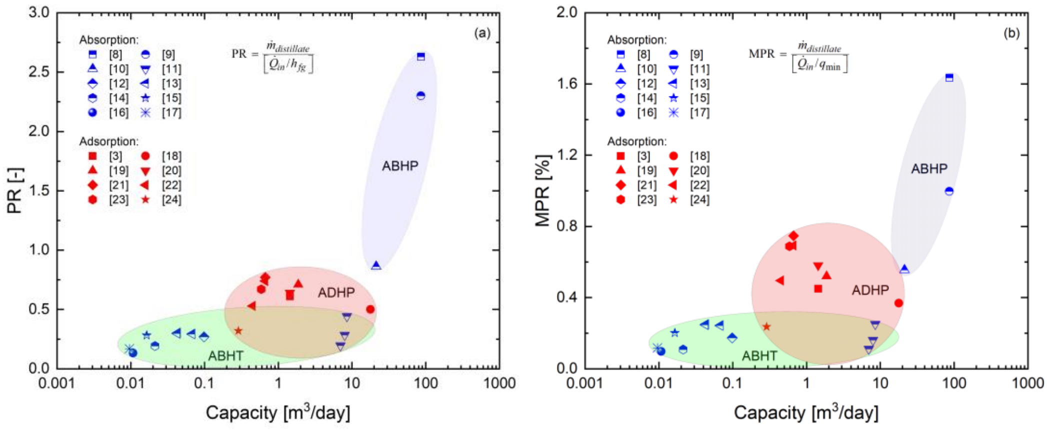

Fig. 2: Comparison between absorption and adsorption desalination systems based on: (a) performance ratio (PR), and (b) modified performance ratio (MPR). Numbers on bars indicate source temperature.

3. Results and Discussion

Figure 1 presents the ABD and ADD systems with single-evaporation effect considered in this study. The temperature of the heat source is shown inside the bars. The environment temperature is taken as the inlet temperature of the saline/impure water. For the studies that did not include this information, $T_0 = 25°C$ is assumed as the reference temperature. Figure 2(a) provides a comparison between these systems based on PR. It can be observed that desalination systems based on ABHT and ADHP do not offer advantage over the desalination by water boiling (PR = 1). On the other hand, ABHP desalination systems have been reported with PR values that are typically 2.5 times higher compared to the boiling process.

Figure 2(b) illustrates that advantage of using MPR as a performance metric by providing a more realistic view. For example, the system presented in Ref [8] has 16.7% higher performance than that of Ref [9] when using PR as a basis of comparison (PR = 2.63 and 2.19, respectively). However, the heat source temperature in Ref [8] is 90 °C, compared to 128 °C in Ref [9] as presented in Fig. 1. This inequality in the energy quality is captured by the proposed MPR. Figure 2(b) reveals that the system in Ref [8] operates at 1.64% of the thermodynamic limits, while the system in Ref [9] is at 1%. This suggests that the system in Ref [8] has actually a 39% higher 2nd law efficiency than the system in Ref [9].

Figure 2(b) also shows that, generally, the desalination systems based on ABHP cycles are more efficient than ABHT. This can be explained by the fact that heat transformers have higher irreversibilites compared to heat pumps. Also, ABHP feature better efficiency compared ADHP except for the design in Ref [10]. The reason for that is the design in Ref [10] does not employ a scheme to recover the heat of condensation as the case in absorption systems in Ref [8] and [9], and adsorption systems in Ref [20]–[23]. It is worth noting that all ABD and ADD systems presented in this study operate 98% below their thermodynamics limits, i.e. MPR < 2%, indicating significant opportunities for performance improvement.

4. Conclusions

The analysis presented in this paper highlighted the importance of using a second-law of thermodynamics metric in performance evaluation of desalination systems. By comparing absorption and adsorption desalination systems in the literature, it can be concluded that the systems that operate based on ABHP are superior to ABHT and ADHP in general. The low MPR values of all the existing systems indicate that there is a great potential to improve the efficiency of desalination systems by reducing irreversible processes.

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