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Water quality assessment of solar-assisted adsorption desalination cycle

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HIGHLIGHTS

- Solar-assisted AD cycle with heat recovery circuit is experimentally investigated.
- Water quality assessment of the pilot AD plant is evaluated by the EPA standards.
- AD process is very effective in eliminating all forms of salts.
- Water quality of AD process is independent of high feed salinity in the evaporator.
- Chemical quality of produced fresh water is comparable to deionized water quality.

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ABSTRACT

This study focuses on the water quality assessment (feed, product and brine) of the pilot adsorption desalination (AD) plant. Seawater from the Red Sea is used as feed to the AD plant. Water quality tests are evaluated by complying the Environmental Protection Agency (EPA) standards with major primary and secondary inorganic drinking water pollutants and other commonly tested water quality parameters. Chemical testing of desalinated water at the post desalination stage confirms the high quality of produced fresh water. Test results have shown that the adsorption desalination process is very effective in eliminating all forms of salts, as evidenced by the significant reduction of the TDS levels from approximately 40,000 ppm in feed seawater to less than 10 ppm. Test results exhibit extremely low levels of parameters which are generally abundant in feed seawater. The compositions of seawater and process related parameters such as chloride, sodium, bromide, sulfate, calcium, magnesium, and silicate in desalinated water exhibit values of less than 0.1 ppm. Reported conductivity measurements of desalinated water are comparable to distilled water conductivity levels and ranged between 2 and 6 μS/cm while TOC and TIC levels are also extremely low and its value is less than 0.5 ppm.

1. Introduction

Over 97.5% of the total worldwide stock of water is saline which constitutes an endless source of drinking water for our planet [1]. Therefore, desalination has been the primary short- and long-term strategic potable water resource choice for many countries around the globe. The cumulative global desalination capacity was estimated to be 68 million m^3 per day in 2010. The Middle East and North Africa (MENA) region contributes to more than 50% of the world's desalination capacity. Furthermore, the world's desalination capacity is expected to reach 120 million m^3 per day by 2020 [2]. The top 10 desalination countries and their estimated capacity per day are shown in Table 1 [3]. Nevertheless, the cost associated with conventional desalination technologies such as multi-stage flash or reverse osmosis makes it difficult for third world countries to adopt desalination as the primary source of potable water. A database of over 300 desalination plants demonstrated that large-scale desalination plants produce water at a cost of \$0.50–\$2.00/m^3, depending on plant size [4]. Furthermore, the dependence of conventional desalination on terrestrial fuel poses a major environmental concern. Desalination plants consume energy for the conversion of seawater to potable water, expressed in terms of electrical equivalent in kW h/m^3, from a supportive dedicated power plant. The energy input to the desalination process is directly proportional to carbon dioxide emission, expressed in kg CO_2/m^3 via the burning of the fossil fuel. Owing to the recovery of waste heat to power the adsorption desalination (AD), it has a specific CO_2 production rate (kg of CO_2 per m^3 of water) of 1/8th of the

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Table 1
The top 10 desalination countries [3].

Country	Capacity (m^3/day)	Share of global production (%)
Saudi Arabia	10,598,000	17
United Arab Emirates	8,743,000	14
United States of America	8,344,000	14
Spain	5,428,000	9
China	2,553,000	4
Kuwait	2,390,000	4
Qatar	2,049,000	3
Algeria	1,826,000	3
Australia	1,508,000	2
Japan	1,153,000	2

conventional multi-stage flash (MSF) or multi-effect distillation (MED) and 1/4 of the reverse osmosis (RO) methods. Here, the AD cycle produces dual useful effects, namely the high-grade fresh water and the cooling capacity [5–13]. For a fair comparison of AD cycle to any desalination methods, therefore, the life cycle costing (LCC) was applied to the cost of processes that produce the same amount of useful effects as the AD cycle [5]. For an AD cycle having a silica gel of 1000 kg as an adsorbent, its performance in producing the two useful effects are 12.5 m^3/day of fresh water and 24 refrigeration tonnes of cooling rate. It was shown that the AD cycle was found to be the lowest cost of US $2.7/MW h (the MW h units have been normalized for the production of dual useful effects), as compared to US$3.7/MW h for the combined RO and absorption chiller and US$4.4/MW h for the combination of a RO plant with a vapor compression chiller. Even though the comparison was made for a small AD plant, the same figures would also be expected from a commercial scale desalination plant.

In this respect, AD has been investigated as a cost effective and environmentally-friendly potable water resource [5–16]. The configured AD cycle employs two pairs of adsorber beds, containing the packed adsorbent (silica gel) in a tube-fin heat exchanger and the components used are mostly stationary other than the flow of heating and cooling fluids being supplied via the three circuits, i.e., the heating, cooling and chilled water circuits. With only a low-temperature heat source from process waste-heat or renewable energy such as solar or geothermal energy, AD cycle utilizes the sorption characteristics of highly porous hydrophilic adsorbent to produce cooling energy and fresh water by desalting seawater or brackish water. AD cycle is batch-operated between adsorption-initiated-evaporation of feed water and desorption-assisted-condensation. The cooling energy is produced from the first phase (evaporation–adsorption) while the fresh water is collected from the second batch process, i.e., desorption–condensation. The primary energy usage in AD cycle is the thermal energy input for the desorption of water vapor from the adsorbents in the desorption–condensation phase. In contrast to the conventional thermal desalination systems such as MSF and MED, the evaporation of feed water (seawater or brackish water) occurs at lower temperatures, typically from 5 °C to 30 °C. The salient advantages of the AD cycle over the other desalination technologies are: (i) it can be powered by a low-temperature heat source, (ii) it has almost no major moving parts, (iii) it has low maintenance, (iv) it is environmentally-friendly, (v) it utilizes zero chemicals in the pretreatment step, and (vi) it can achieve high recovery ratio. Wang and Ng [6] reported that the specific daily water production (SDWP) of the AD plant using a four-bed regeneration scheme can be expected to be approximately about 4.7 kg/kg of silica gel at half-cycle time of 180 s while the inlet temperatures of hot, cooling and chilled water are held at 85 °C, 29.4 °C and 12.2 °C, respectively. It has been demonstrated that the AD plant is also functional when the heat source temperature is lowered to 65 °C. Thu et al. [7] investigated experimentally the optimum operating cycle times at different hot water inlet temperatures and highlighted the importance of suitable operation cycle time at different hot water inlet temperatures. It was also noted that significant improvement in SDWP is achieved by four-bed operation mode as compared to two-bed mode at high hot water inlet temperatures. The performance of a waste heat-driven four-bed AD cycle had been investigated both numerically and experimentally by Ng et al. [8]. They showed that the SDWP and the specific cooling power (SCP) of the AD cycle can be achieved up to 8 m^3 and 51.6 Rton per tonne of silica gel per day and the AD cycle has an overall conversion ratio (OCR), defined as the ratio of total useful effects (cooling energy and potable water) produced over the heat input of the cycle, of about 1.4 since it produces two useful effects, namely, the cooling and fresh water from a single heat input. Also, an advanced AD cycle with condenser–evaporator heat recovery scheme utilizing an encapsulated evaporator–condenser unit for effective heat transfer has been developed and its performance was examined numerically for assorted heat source and cooling water temperatures [9]. In addition, an investigation on the efficacy of a silica gel-water based advanced AD cycle with internal heat recovery between the condenser and the evaporator was carried out experimentally and numerically [14–16]. It was found that the SDWP of the AD cycle is about 9.34 m^3 per tonne of silica gel per day at a regeneration temperature 70 °C and the corresponding performance ratio is 0.77 which implies that the AD cycle with evaporator–condenser heat recovery circuit is an efficient cycle. Recently, it has been reported that the AD cycles can be synergistically hybridized with various thermal-desalination processes such as MED and membrane distillation (MD) for unprecedented improvement in water production capacity [17,18].

Therefore, it has been proved that AD process is an environmentally-friendly and yet low-cost desalination method utilizing low-temperature heat source derived from either the waste heat or renewable energy. As shown in the aforementioned literature, however, much work related to the thermodynamic framework and operational improvement schemes for the AD cycles have been reported. Most of previous studies on the AD cycle have been carried out only to evaluate and optimize the performance of AD process using a potable water or simulated seawater. Furthermore, there is dearth of literature concerning the chemical quality of brine and product water from the AD process with raw seawater.

This study investigates the desalinated water quality by various chemical testing of samples collected with respect to brine level in the evaporator, namely, 26% (exposure of all tubes), 40% (exposure of half tubes) and 50% (immersion of all tubes), of the solar-powered AD pilot plant at the King Abdullah University of Science and Technology (KAUST), Saudi Arabia. This is because the brine level in the evaporator of AD plant affects greatly on the brine quality (concentration), which is attributed to the different evaporation mechanisms such as spray-mode of evaporation, pool boiling and thin-film evaporation. Here, the brine quality is one of the sources (i.e., feed seawater salinity, demister design and maintenance, materials of the evaporators and their associated equipment, raw seawater pollutants or pollutants formed during pretreatment, pollution from maintenance and repair activities, leakage at all equipment parts, etc.) influencing on the quality of the fresh water produced in the conventional desalination processes. The ultimate purpose of this paper is to describe the fundamental process of fresh water production and to highlight the chemical quality aspect of feed water and product water at the pretreatment stage.

2. Experimental

2.1. Adsorption desalination pilot plant

Fig. 1 shows a schematic and pictorial view of the solar-powered AD pilot plant at the KAUST, Saudi Arabia. The AD cycle employs the internal heat recovery between the condenser and the evaporator by a heat recovery circuit [5,14–16], as depicted in the green line in Fig. 1(a). The plant comprises of two sub-systems: solar-thermal system and AD system. The solar-thermal system consists of the flat-plate collectors of 485 m^2 and the solar hot water tanks of 3 m^3 each where the