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A new approach to thermo-economic modeling of adsorption desalination system

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ABSTRACT

The mathematical model for the prediction of an adsorption desalination system (AD) performance with heat and mass recovery was presented. This analysis resulted in the determination of the thermodynamic properties at different points and the specific daily water production value. The computational model based on the mass and heat transfer concept was developed to predict the performance of AD system. Then, the irreversibility analysis was performed, and exergy destruction (considering chemical and physical exergy) was calculated. The exergoeconomic analysis of AD system was implemented. Total revenue requirement method was used in the economic investigation of the scheme. The validated model indicated the water production rate as well as the water production cost. The permeate flow rate in the system was obtained to be 51.3 kg/s. The AD system specific daily water production increased up to 11.92. The optimal exergetic efficiency of the system and the cost of water production were calculated to be 5.9% and 0.57 US $ per cubic meter respectively.

1. Introduction

The scarcity of fresh water is one of the challenges of many countries. About 40% of people in the world are suffering from freshwater shortages [1]. In arid and desert areas, brine or seawater desalination to supply permeate water is the only satisfactory solution. Use of renewable energy and waste heat from power generation plants to reduce the energy consumption and cost is considered as a suitable solution. Sarwar et al. [2] investigated the phase change materials specifications and showed that these materials are ideal for their application as a multi-stage flash and multi-effect distillation processes of non-membrane based indirect solar desalination systems. Carrasquer et al. [3] presented the exergy cost analysis for water desalination and purification techniques by transfer functions. Elminshawy et al. [4] investigated the techno-economic feasibility of using the hybrid solar-geothermal energy source in a humidification-dehumidification (HDH) desalination system. Their advanced HDH system was a modified solar still with an air blower and condenser used at its inlet and outlet respectively. They analyzed the system analytically to compare the effect of solar energy and combined solar-geothermal energy on producing. Deniz et al. [5] presented a new humidification-dehumidification (HDH) solar desalination system. They designed and tested the system with the actual conditions, and solar energy was applied to supply both thermal and electrical energy. They conducted energy and exergy investigation as well as the economic and environmental analysis of a solar desalination system. Ismail et al. [6] analyzed the performance of two sequential desalination systems, Multi-effect distillation and mechanical vapor compression with renewable energy resource. They presented that site location, wind speed, solar intensity, ambient temperature, and water salinity are the most critical factors in the performance of the system. Kabeel et al. [7] studied the two solar stills to assess the yield and energy performance of an advanced passive solar desalination system in comparison with a conventional one. This improved still is connected to a latent heat thermal energy storage medium and a parabolic solar concentrator. They used phase change material (PCM) in the solar still bottom plate. They presented a mathematical analysis for the calculation of the exergetic proficiency. They tested the system experimentally. Desalination methods divided to thermal and membrane desalination systems. Adsorption desalination is a thermal system. The performance improvement of adsorption desalination system was studied by Ng and his research team [8–10] at the laboratory scale based on system structure and function of the operating parameters. They investigated the performance of a solar-assisted adsorption (AD) cycle, which produced the cooling, and desalination

Abbreviations: AD, Adsorption Desalination; CELF, Constant-escalation levelization factor; c_p, Exergoeconomic price [$/m^3]; CRF, Capital recovery factor; FC, Fuel Cost; ITX, Income Taxes; LMTD, Logarithmic mean temperature difference; MAR, Minimum Acceptable Return; OMC, Operation and maintenance cost; OTXI, Other Taxes and Insurance; PEC, Purchased Equipment Cost; ppm, Part per million; ROI, Minimum Return On Investment; sg, Silica gel; SWDP, Specific Daily Water Production (kg_w/kg_{sg} day); TCR, Total Capital Recovery; TRR, Total Revenue Requirement; w, Water

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Nomenclature

Cp	Specific heat (kJ/kg)
D	Permeate water (kg/s)
D_{so}	Pre-exponential constant
e	Exergy (kW)
E_a	Activation energy
G	Gibbs energy
h	Enthalpy (kJ/kg)
i_{eff}	Average annual effective discount rate
K_0	Pre-exponential constant
M	Mass flow rate (kg/s)
n	Book life (year)
P	Pressure (kPa)
q^*	Uptake value at equilibrium conditions
q_∞	Monolayer (adsorption) capacity
R_p	Adsorbent particle radius
R	Constant escalation
S	Entropy (kJ/kg K)
t	Toth constant
T	Temperature (K)
X	Concentrate (ppm)

Greek letters

μ_0	Chemical potential
ρ	Density
ΔH_{ads}	Isosteric enthalpy of adsorption
τ	Total annual time of system operation (hours)

effects, with a low-temperature heat input such as solar energy. Then, they studied the adsorption desalination (AD) cycle with internal heat recovery between the condenser and the evaporator. Also, they analyzed the performance of a waste heat-driven adsorption cycle. The advantages of the adsorption method include:

- Using the heat of low thermal value
- Low maintenance costs
- Low fouling and corrosion
- Ability to simultaneously produce fresh water and cooling effect
- Providing a non-contaminated product

Thermodynamic modeling and performance analysis (performance parameters including bed temperature and bed pressure) of AD cycle was performed by Thu et al. [11]. An overview of the modeling and simulation cycle theory AD in [12–16] is given. Wang et al. studies [13] in 2005 showed that the AD unit could produce about 4.7 kg water/(kg of silica gel) and the chilled water temperature was 12.5 °C. With continued research by Ng and his team [17,18], the new MEDAD method was introduced. This method was able to improve the performance of the MED system to overcome the limitations of current methods. This approach will allow the temperature of the last effect of MED could reduce to below the ambient temperature. It does not only reduce the possibility of corrosion but also increases the production of distilled water by 2 to 3 times. Ng et al. [19] reviewed the state-of-art of adsorption desalination over the past years. They investigated the hybridization of the adsorption and nanofiltration (AD-NF) processes and conventional MED processes (AD-MED). Thu et al. [20] presented a numerical model for the mass recovery scheme by pressure equalization for adsorption desalination systems. They improved the specific daily water production (SDWP) as high as 5% by the mass recovery scheme and compared it with experimental results. Yusuf et al. [21] examined the condenser and the evaporator temperature effect on the adsorption desalination cycle performance. They showed that reducing the temperature of the condenser and increasing the evaporator temperature could increase the amount of fresh water. Ali et al. [22] examined an adsorption desalination system with two adsorbents (silica gel and zeolite). They found that the silica gel in water production systems and the zeolite for cooling systems were suitable options. Youssef et al. [23] modeled a four bed combined adsorption desalination and cooling cycles. They studied the effect of condenser temperature. Thu et al. [24] investigated the performance of the multi-bed AD cycle with internal heat recovery between the condenser and the evaporator. They reported the experimental data for such cycle for the first time using 50 °C to 70 °C heat sources. Ali et al. [25] studied the solar adsorption desalination-cooling system theoretically. They presented the performance analysis for the investigating system around the year. Ng et al. [26] proposed an exergy approach for the evaluation of desalination process efficiency based on the consumption of primary energy. Shahzad et al. [27] reviewed state of the art of energy, water and environment relation and future energy efficient desalination process to save the energy and the environment. Mitra et al. [28] analyzed a solar driven adsorption desalination process. They showed that the single-stage AD process has an optimum half cycle time in the range of 600–900 s for the maximum desalination capacity. Li et al. [29] performed an experimental study for the testing processes to achieve the best efficacy of adsorbent-binder coated exchangers. They presented 3.4–4.6 folds improvement in heat transfer rates over the common granular-packed method, which resulted in a higher rate of water transport by 1.5–2 times on the suitable silica gel type. Missimer et al. [30] proposed a new process combination for geothermal electricity generation and desalination. They found that the concept of the geothermal- powered electric desalination-storage "campus" facility has the potential to prepare a completely renewable process with a very high efficiency. Saha et al. [31] presented the review of the recent development of the adsorption desalination system and its hybridization with the conventional desalination process. They measured the adsorption isotherms and kinetics of different adsorbent/refrigerant pairs by a magnetic suspension adsorption measurement unit. Shahzad et al. [32] investigated the heat transfer behavior for evaporative film boiling on horizontal tubes with low pressure ranges from 0.93–3.60 kPa. Shahzad et al. [33] proposed the advanced desalination process that hybridizes a conventional multi-effect distillation (MED) and the low-energy adsorption desalination cycle (AD). They found that the hybridization of MED and AD enhanced the water production more than three folds with same top brine temperature as compared to traditional MED plants. Shahzad et al. [34] investigated the thermally driven MEDAD hybrid desalination system, experimentally. Shahzad et al. [35] proposed an advanced hybrid desalination cycle called "MEDAD" desalination which is a hybrid of the multi-effect distillation (MED) and an adsorption cycle (AD). They presented the experiments of a 3-stage MED and MEDAD plants. Shahzad et al. [36] presented experimentally the synergetic effect between the adsorption desalination and MED cycles that improved the water production. Thu et al. [37] investigated the hybrid AD and MED cycle for increased performance for water desalting. They presented a detailed numerical model for analyzing of the transient behaviors of heat and mass transfer in the combined AD and MED cycles. Shahzad et al. [38] proposed a tri-hybrid system (RO + ME-AD) to increase the overall recovery. They indicated that their system has the lowest specific energy consumption as compared to other systems. Shahzad et al. [39] investigated the efficacy of a multi-effect distillation (MED) system operated with the thermocline energy from the sea. Shahzad et al. [40] proposed a hybrid desalination cycle by integrating multi cascaded-evaporators with an adsorption desalination cycle to improve the performance ratio (PR) of the cycle. Mitra et al. [41] analyzed the two-stage adsorption desalination (AD)