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Integration of humidification-dehumidification desalination and concentrated photovoltaic-thermal collectors: Energy and exergy-costing analysis

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ABSTRACT

Water desalination by humidification-dehumidification-humidification (HDH) cycle is considered as a viable option for small-scale freshwater production in remote areas. When integrated with solar power generation units, this stand-alone co-generation system would become very attractive for reliable simultaneous freshwater and electrical power production. This study evaluates the performance of a co-generation unit based on integration of air-heated HDH desalination cycle with concentrated photovoltaic-thermal (CPVT) collectors. Mathematical model for integrated system under steady-state conditions has been presented. Exergy-costing method was applied to estimate the cost of system's products. The results show that the system would be able to produce 12 m^3 of freshwater and 960 kWh of electricity per year for a site having 1.88 MWh/yr solar irradiance. The unit cost for freshwater production and electrical power generation is estimated as 0.01 $/L and 0.289 $/kWh, respectively.

1. Introduction

Water desalination by Humidification-Dehumidification-Humidification (HDH) is an interesting technology that mimics the nature for production of fresh potable water. HDH-based desalination systems are considered a viable option to meet the freshwater demand in the arid and remote areas where the supply through pipelines, or by transportation is prohibitive [1]. They are simple in design and operation; therefore require moderate operational and maintenance cost. They are modular which means they provide flexibility in capacity. In addition, low-temperature energy sources, such as waste heat [2,3] and solar energy, can be utilized for operation of HDH systems [4].

Other thermal desalination technologies such as Multi-Stage-Flashing (MSF) and Multi-Effect-Desalination (MED) are not economically feasible for small-scale production and demand complex installation and operation as they work under vacuum conditions and high temperatures [5]. Membrane processes, such as Reverse Osmosis (RO), which is considered the most economical desalination system, require continuous supply of electricity for operation which might not be available in remote areas. All the above-mentioned aspects shift the attention to solar-driven HDH system for small-scale decentralized desalination [6].

Depending on the heated fluid medium, HDH can be classified as water-heated or air-heated. Water-heated solar HDH has been widely investigated, experimentally and numerically, by many researchers. Soufari et al. [7] tested an experimental solar-HDH unit based on theoretical model presented in Ref. [8]. Flat-Plate (FP) solar collectors were used to heat saline water in the aim to produce 10 L of freshwater per hour. The experimental results were in good agreement with the theoretical model, and the authors reported that although the optimization procedure was based on a cost-effective design, the productivity is increased by 4% compared to previous design [8,9]. Wang et al. [10] studied the performance of water-heated HDH unit powered by photovoltaic (PV) cells. The system was designed to meet the freshwater daily demand of four adults family (2 l/adult per day) by 9.16 m^2 PV panels. The experimental results revealed that the annual production was significantly overestimated by the theoretical analysis. Zamen et al. [11] experimentally explored the enhancement of productivity by multi-stage HDH cycle. A pilot plant, with two-stages and comprises 80 m^2 FP collectors, was built and results indicate a 20% increase in the productivity compared with single-stage cycle. Hamed et al. [12] presented a mathematical model for HDH cycle heated by Evacuated-Tube (EVT) water collector. The aim of the study was to enhance the heat recovery from vapor condensation on the dehumidifier. The model was validated by experimental data from a test rig, and the average productivity is estimated as 22 L/day.

In contrast to water-heated cycle, there is no much studies that investigated air-heated HDH cycles [1]. Solar collectors represent about

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40% of the total cost of solar integrated HDH systems [13]. Having simpler design, solar air collectors provide great opportunity to reduce this cost significantly. Antar and Sharqawy [14] conducted an experimental study to evaluate the performance of air-heated HDH unit that can work on both single and two-stage modes. Solar EVT collectors were used for heating the air in the cycle. The authors reported that heat losses and pressure drops in pipelines and fittings would result in a significant temperature drop of air. Li et al. [15] carried out experimental study to examine the performance HDH air-heated pilot plant with a new design of dual-wall glass EVT air collector.

Zhani et al. [16] suggested simultaneous use of air solar and water collector in HDH systems. The authors developed a mathematical model, validated by experimental data, to predict the thermal performance of conventional solar FP air and water collectors in HDH system. Yuan et al. [5] conducted experimental study on HDH pilot plant that produces 1000 L/day for an averaged solar irradiance of 500 W/m^2. The heat input to the air is provided by means of 72 EVT collectors (100 m^2), while ten solar water heaters (14 m^2) were used to enhance the water evaporation. Bacha [4] presented a dynamic model for HDH powered by FP air and water solar collectors to allow the system to be more flexible during intermittent and low solar irradiance periods. An experimental prototype was built, consisted of six (2 × 1 m) water collectors and eight (8 × 2 m) air collectors, to validate the theoretical model. The experimental data were found to be in a good agreement with simulation results. Yıldırım and Solmuş [17] developed a mathematical model to study solar-driven HDH cycle operating on water, air, and hybrid water/air heating modes under different climatic conditions. The solar water heater considered in the analysis was basically a 2 m^2 FP collector, while a double-pass air collector of 2 m^2 is used for air heating. It was observed that there is an optimum air flow rate value at which the daily water production is maximized. Deniz and Çınar [18] conducted energy and exergy analysis for an experimental solar-only HDH desalination unit. FP solar air and water collectors were used to provide the heating power, while a PV panel was used to supply the required electrical power for the unit. Evaluation of dual-purpose collector in HDH systems has been presented in [19,20].

In remote areas, co-generation systems would be of great interest to generate multiple products from a single unit. Some studies explored combining HDH with cooling plant [21], air conditioning units [22,23] and power generation [24,25]. Giwa et al. [24] investigated the technical and environmental aspects of integrating solar photovoltaic-thermal (PVT) air collector in HDH for small-scale combined power and freshwater production. The simulation results showed that the system could produce 2.28 L of freshwater per squared meter of PV area, and would decrease the environmental impact by 83.6% when compared with PV-Reverse Osmosis system.

From the literature survey, it is observed that there is a scarcity of information about air-heated HDH cycles, and about integration of PVT collectors with HDH units. PVT collector is considered as a feasible and reliable solution for simultaneous electrical and thermal power. Thermal and electrical gain from PVT systems can be increased by integrating compound parabolic concentrator (CPC), which results in a compact concentrated PVT (CPVT) collector. To the author knowledge, there is no study up to date considered integration of air CPVT collectors with HDH cycles. Therefore, the aim of this study is to investigate the performance of an air-heated HDH-CPVT co-generation unit for freshwater and electrical power production. Moreover, this is the first study that considers applying exergy-costing method to HDH cycles to evaluate the unit cost of system's products.

2. Mathematical modeling

A schematic diagram of the proposed HDH-CPVT air-heated desalination system is shown in Fig. 1. The system is mainly composed of CPVT array, humidifier, dehumidifier, water pump, air fan/blower, Maximum Power Point Tracking (MPPT) controller, battery and inverter. The model for HDH-CPVT integrated system is developed under the following assumptions:

- One-dimensional steady-state model;
- Neglected heat losses from ducts/pipes, humidifier, dehumidifier and sides of CPVT collectors;
- The condensed water in the dehumidifier is at temperature that equals the average of the exit air's dry-bulb temperature and dew-point temperature of air at the inlet [26];
- Negligible enthalpy difference between upstream and downstream of pump/fan;
- No leakage of air from the system;
- The inlet feed seawater is at 22° C temperature and have 35 g/kg salinity;
- The freshwater and brine exist at 0 and 35.5 g/kg salinity, respectively;
- Only 75% of gross electricity generated by PV is available (due to electrical mismatch, transmission losses in wires, and to avoid complete discharge of batteries);
- The power consumed by pump and fan is 25 W and 50 W, respectively.

2.1. CPVT collectors

The CPVT collectors considered in this study are double-pass air collectors Fig. 2. The air flows in the upper channel to collect the heat from the upper surface of PV/absorber. Further heating is achieved through passing the air in a lower channel. Fins are attached at the backside of the PV/absorber surface to enhance the heat transfer. A compound parabolic concentrators, with 2X concentration, are used to increase the intensity of solar irradiance. The CPVT array is composed of three modules connected in parallel, with each module having four collectors of 0.25 m × 3 m (W × L) dimensions, making a total surface area of 9 m^2 (The total area of PV cells is 4.5 m^2) as demonstrated in Fig. 3.

The steady-state energy balance equations applied to different components of a CPVT collector (fully covered with PV cells) in the positive direction x are given as follows [27]:

$$\text{Upper cover: } S_{g1}+h_{r,g2-g1}(T_{g2}-T_{g1})=h_{r,g1-sky}(T_{g1}-T_{sky}) + h_{c,g1-wind}(T_{g1}-T_{amb})+h_{c,g1-f1}(T_{g1}-T_{f1}) \tag{1}$$

$$\text{Lower cover: } S_{g2}+h_{r,pv-g2}(T_{pv}-T_{g2})=h_{r,g2-g1}(T_{g2}-T_{g1}) + h_{c,g2-f1}(T_{g2}-T_{f1}) \tag{2}$$

$$\text{Upper channel: } \frac{\dot{m}C_p}{W_2}\frac{dT_{f1}}{dx} = h_{c,g2-f1}(T_{g2}-T_{f1}) + h_{c,g1-f1}(T_{g1}-T_{f1}) \tag{3}$$

$$\text{Lower channel: } -\frac{\dot{m}C_p}{W_2}\frac{dT_{f2}}{dx} = h_{c,pv-f2}(T_{pv}-T_{f2}) + h_{c,bp-f2}(T_{bp}-T_{f2}) \tag{4}$$

$$\text{PV/absorber: } S_{pv}(1-\eta_{el})=h_{r,pv-g2}(T_{pv}-T_{g2})+h_{c,pv-f2}(T_{pv}-T_{f2}) + h_{r,pv-bp}(T_{pv}-T_{bp}) \tag{5}$$

$$\text{Back plate: } h_{r,pv-bp}(T_{pv}-T_{bp}) = h_{c,bp-f2}(T_{bp}-T_{f2}) + U_b(T_{bp}-T_{amb}) \tag{6}$$

Here, $\dot{m}$ is the mass flow rate and C_p is the heat capacity of the fluid. S is the fraction of total incident irradiance intercepted by CPC ($I_{t,CPC}$) and absorbed by different components. Important equations to model the performance of CPC are given in Appendix A. h_c and h_r are the convective and radiative heat transfer coefficients. The subscripts $g1$, $g2$, pv, bp, $f1$ and $f2$ refer to upper cover, lower cover, PV cells, back plate, air in the upper and lower channel, respectively. U_b is the loss coefficient at bottom insulation, and η_{el} is the electrical efficiency of PV module. The lower letters "*amb*", "*wind*" and "*sky*" stand for ambient, wind and sky, respectively. The thermo-physical parameters of the considered CPVT collectors and complete electrical modeling approach