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Research paper

Humidification dehumidification desalination system using parabolic trough solar air collector

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HIGHLIGHTS

- Thermodynamic analysis of an HDH system driven by a parabolic trough solar collector was conducted.
- The first configuration reveals a GOR of 1.5 while the second configuration reveals a GOR of 4.7.
- Effective heating of the HDH system was obtained through parabolic trough solar collector.

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ABSTRACT

This paper deals with a detailed thermodynamic analysis to assess the performance of an HDH system with an integrated parabolic trough solar collector (PTSC). The HDH system considered is an open air, open water, air heated system that uses a PTSC as an air heater. Two different configurations were considered of the HDH system. In the first configuration, the solar air heater was placed before the humidifier whereas in the second configuration the solar air heater was placed between the humidifier and the dehumidifier. The current study revealed that PTSCs are well suited for air heated HDH systems for high radiation location, such as Dhahran, Saudi Arabia. The comparison between the two HDH configurations demonstrates that the gained output ratio (GOR) of the first configuration is, on average, about 1.5 whereas for the second configuration the GOR increases up to an average value of 4.7. The study demonstrates that the HDH configuration with the air heater placed between the humidifier and the dehumidifier has a better performance and a higher productivity.

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1. Introduction

Although the availability of water is abundant in the world, pure consumable water is a scarce resource. Most regions with scarcity of water are dry regions, where abundant solar energy is available. Therefore, desalination assisted by a solar energy technology is a viable option within such regions. Using a renewable energy resource for desalination is suitable for rural and remote areas and it is a preferred technology over fossil fuels. This allows the improvement of the living conditions with a very minimum impact on the environment. Solar energy technologies have had extraordinary development within the past two decades, where many improvements such as concentrating technologies, among others, have been introduced [1].

Different methods are available for desalinating saline water through a thermal process. The basics of the thermal process, requires the saline water to be vaporized where the fresh water is collected. Examples of such technologies that use such process are multiple effects, multi-stage flash and more recently humidification dehumidification process. One of the main problems faced with these technologies is relatively high demand of energy due to the vaporization phase change [2].

A number of studies were conducted to analyse the performance of water desalination using solar energy, e.g. Refs. [3–6]. Performance assessment of a small-scale multi-effect distiller for an optimized solar thermal desalination was carried out by Joo and Kwak [3]. They found that the performance ratio of their system was around 2.0. The performance assessment of v-trough solar concentrator for desalination applications was investigated by

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Riffat and Mayere [4]. They showed that a thermal efficiency of 38% was obtained when the heat transfer fluid temperature reaches 100 °C at the outlet of the concentrator. In addition, they concluded that the v-trough solar concentrator is a promising solution for small and medium water desalination applications. In a different study, performance evaluation of combining desalination systems with concentrated solar power plants was conducted by Palenzuela et al. [5]. They concluded that a low temperature multiple-effect distillation is more efficient than a low temperature multiple-effect distillation integrated with a thermal vapour compression. In another study, a dynamic model of a solar system assisted a multiple-effect distillation system was investigated by Calle et al. [6]. The model can be used to optimize the operating control of such systems.

Humidification dehumidification (HDH) desalination process is regarded as a favourable technique for small water capacity production plants. The main attraction towards this process is its capability to operate at low temperatures, the use of low-level technical features, and the possible integration of sustainable energy sources. In addition, one of the greatest advantages with this process of desalination is that it uses separate components for each thermal process, which in turn allows each individual element to be independently designed. Hence, it allows much greater flexibility with the thermodynamic cycle for vaporizing water into air and consequently condensing the vapour [7]. An HDH desalination system when compared with solar stills has significantly higher gained-output-ratio (GOR), which results in reducing the total area of the solar collector required for a given water demand. The GOR is defined as the ratio of the collected fresh water multiplied by the water enthalpy of vaporization to the energy input of the system. HDH systems are more suitable for the developing world in terms of the capital investment and limited technical support. Subsequently, it involves relatively inexpensive and simple mechanisms that can also operate under a wide range of raw water quality without the need for complex maintenance operations. The foremost downside of the HDH systems is the relatively high thermal energy requirement in comparison to other technologies. Therefore, there is a need for further research to improve the performance of the HDH desalination systems.

Solar stills generally integrate the functions of solar collection, water heating, evaporation, and condensation into a single system. Such systems result in a considerable thermal inefficiency. As a result, solar stills normally have a low GOR and require relatively large areas in order to produce fresh water. Alternatively, the HDH desalination systems overcome some of the shortcoming of the solar stills and consequently they have higher GOR.

The classification of HDH systems is generally dependent on whether air or water is heated and if the air and/or the water flow through an open or closed loop. There are various experimentations in using a combination of both air and water heaters, or the use of steam generators and water storage tanks, or the use of a combined humidifier and dehumidifier in place of two separate units. Table 1 shows a comparison of some of the experiments carried out on various HDH systems where the mode of heating is the main difference amongst them.

Thermodynamic analysis of an HDH system is generally based on energy and mass balances of each individual component within the system. Narayan et al. [17] and Mistry et al. [18] showed that the top water temperature and mass flow rate ratio of air and water streams play a major role in identifying the maximum GOR in an HDH system.

Some of the existing HDH thermal desalination technologies were discussed by Narayan et al. [19]. Some of the HDH systems discussed in their study were multi-stage air heated cycle, mechanical compression driven cycle, HDH with thermodynamic balancing, HDH with common heat transfer wall, and hybrid HDH system with reverse osmosis, among others.

Ettouney [20] evaluated the characteristics of four layouts of HDH systems. A common feature among these layouts was the air humidification tower that had been used to increase the ambient air humidity to saturation at the desired design temperature. The main difference among the various layouts was the process of dehumidification. One layout used a condenser to reduce the temperature of the humidified air and to condense the fresh water product. The other configurations considered were membrane air drying, desiccant air drying, and vapour compression. The main drawback stressed upon was the presence of air in bulk along with water vapour. The dehumidification process efficiency had drastically reduced due to the above mentioned reason.

Wang et al. [21] studied a photovoltaic (PV) driven humidification dehumidification desalination system. The main factors affecting the evaporation and condensation were considered in their study. The rate of evaporation of water and the condensation of the mass flow rate increase along with the increase of evaporative raw water. In addition, the condensation rate was found to increase with lower cooling water temperatures. While the aforementioned parameters were set to their optimal levels, it was also found that the forced convection method had a higher yield of fresh water in comparison to the natural convection, A recent humidification dehumidification desalination technology known as humidification compression was presented by Ghalavand et al. [22]. The main characteristic of this technology is the polytropic compressor where no heater is required.

Table 1
Comparison of different desalination system.

Heating mode	Production	Comments	Reference
Air heating (evacuated tubular solar water heater)	4 kg/m^2-day (increased to 10 kg/m^2-day including the water heating)	Single stage, double pass solar collector, pad humidifier and finned tube dehumidifier and 0.5 m^3 water storage tank. No heat recovery. Water may be heated in the storage tank to increase the production significantly.	Yamali and Solmus [8,9]
Air heating	4 L/m^2-day (total 516 L/day)	Five heating-dehumidification stages; Forced air circulation; total collector area – 127 m^2	Houcine et al. [10]
Air heating	Up to 5 kg/h (GOR < 4)	Natural and forced air flow, heat recovery in the condenser	Nawayesh et al. [11]
Water heating	8 L/m^2-day (GOR < 2)	2 m^2 solar collector area, humidifier and condenser specific areas are 14 and 8 m^2	El-Hallaj et al. [12]
Water and air heating	9 L/day	Packed bed humidifier, air cooled dehumidifier	Nafey st al. [13]
Water heating	13 L/m^2-day (GOR = 3–4.5)	Thermal storage, natural air draft, 38 m^2 collector area	Muller-Holst et al. [14]
Water heating	12 L/m^2-day (GOR < 4)	Forced circulation of air, multi-pass shell and tube condenser and wooden shaving packing in the humidifier.	Farid et al. [15]
Water heating	3 L/m^2-day (GOR < 0.5)	Solar area 6 m^2. No energy recovery.	Ben Basha et al. [16]

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