Desalination 441 (2018) 52–61

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

# Performance evaluation of a humidification–dehumidification unit integrated with wick solar stills under different operating conditions

A.S. Abdullah[a,c], F.A. Essa[b], Z.M. Omara[b,*], M.A. Bek[c]

[a] Mechanical Engineering Department, College of Engineering, Prince Sattam bin Abdulaziz University, Saudi Arabia
[b] Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt
[c] Faculty of Engineering, Tanta University, Egypt

ARTICLE INFO

*Keywords:*
HDH
Desalination
Humidification-dehumidification
Wick solar still

ABSTRACT

A comprehensive hybrid distillation system of humidification and dehumidification (HDH) unit incorporated by six wick solar stills was designed, fabricated, combined, and experimented to investigate the system performance. In the humidifier, different packing materials (aspen pad and thorn trees) and various water flow rates (1, 2, 3, and 4 kg/min) were investigated. The generated vapor in the humidifier was forced to be condensed in the dehumidifier. The desalination system was tested during the day- and night times. Performance of the wick stills was evaluated. The wick stills were fed by the brine hot water ejected from the HDH unit. Results revealed that using the aspen pad inside the humidifier provided greater freshwater productivity than that of the thorn trees. HDH unit packed with aspen pad at 4 kg/min produced the greatest distillate. At 4 kg/min, average gained output ratio (GOR) was raised from 2.5 for HDH unit working through the daytime only to 4.5 for the same unit operating through the day- and night times. Additionally, the hybrid system obtained a doubled productivity compared to HDH unit only, and the overall average GOR was increased from 5.1 to 5.7 with increasing the water flow rate from 2 to 4 kg/min.

## 1. Introduction

One of the easiest and effective methods of thermal distillation systems is humidification–dehumidification (HDH). HDH desalination systems have many advantages such as the simple structure, no fuel consumption, the ability of heat recovery, low-temperature operation, no complicated technology requirements, the capability of other renewable energy systems' integration, and finally the separate and independent parts for each process. These advantages make the HDH more flexible and commoner among the other thermal desalination systems [1].

Hisham [2] presented an evaluation of the characteristics of several layouts of HDH desalination process. The most common scheme was to use a condenser to reduce the humidified air temperature and to condense the freshwater product. Other layouts included vapor compression, desiccant air drying, and membrane air drying. The design equations were developed for the humidification/condenser and humidification/desiccant systems. Discussion and performance evaluation of various layouts showed the need to fully optimize these configurations. This is necessary to obtain the best design and operating conditions that give the minimum product cost. Karan et al. [3] applied irreversibility analysis to characterize the HDH desalination cycles and to identify how to further improve the cycles and components. They found that minimizing the specific entropy generation of the cycle maximizes the gained output ratio (GOR). Various types and design improvements of HDH desalination system were reviewed in detail by Adewale et al. [4]. They found that the HDH desalination process is a promising technique for producing freshwater to meet localized water demand. The overall thermal energy needed to operate the HDH system can be obtained from renewable sources like solar and geothermal energies, as it is a low-temperature process. However, most HDH systems in current and previous studies are powered by solar energy.

A hybrid solar desalination system comprising a humidification-dehumidification unit and solar stills was investigated in an attempt to improve the performance of solar desalination system. Where the drain warm water from the humidification-dehumidification unit was reused to feed the solar stills to prevent massive water loss during the desalination process. Fath et al. [5] evaluated the performance of a solar still integrated with HDH system with open-water and closed-air loops. The effect of design and operational parameters on the water production was studied numerically. Results indicated that increasing the ambient temperature, solar intensity, basin absorptivity, and initial saline water

* Corresponding author.
*E-mail address:* zm_omara@yahoo.com (Z.M. Omara).

https://doi.org/10.1016/j.desal.2018.04.024
Received 18 December 2017; Received in revised form 19 April 2018; Accepted 21 April 2018
0011-9164/ 

temperature increased the system productivity. On the other hand, increasing the basin insulation thickness, wind velocity, evaporation and condensation surface areas, condenser emissivity, and saline water mass had a little effect on the productivity. Furthermore, decreasing the HDH air flow rate had insignificant influence on the system productivity. In addition, Fath et al. [6] developed a solar distillation system of integrated conventional solar still with HDH sub-system. They indicated that the circulation of natural air could replace the circulation of forced air and simplify the system complexity and economy. Furthermore, the productivity was found to be 10 kg/m$^2$ a day, which was almost the double of the conventional solar still productivity. To overcome the limitations associated with conventional solar still, Sharshir et al. [7] reported theoretically that the daily production of the conventional solar still with the exit warm water from HDH system was greater than that of the conventional solar still. It was found that the daily productivities of the conventional still alone and conventional still with exit warm water from HDH unit were 3.6 and 8.2 L/day, respectively.

A new solar-driven desalination system was developed by Amir et al. [8]. The test-rig included a hybrid solar still/two effects HDH desalination system combined with solar concentrator and two thermally cooled photovoltaic panels. The system performance was investigated theoretically under different operating conditions such as different basin water heights, air mass flow rates, and solar concentration ratios. They found that the system productivity was decreased with increasing the basin height and the circulating air mass flow rate. In addition, integrating the photovoltaic panels along with solar concentrator led to a significant increase in the freshwater productivity at high concentration ratio. A solar water desalination system with HDH cycle was designed and integrated with a solar still (as a solar humidifier) and a new subsurface condensation mechanism [9]. Results indicated that the rate of water production reached above 264.86 kg/day and the produced water, passing through the pores on the tubes, could be used to irrigate plant roots or collected as a drinking water. Coupling of a cascade solar still with a humidification-dehumidification system was investigated experimentally by Tabrizi et al. [10]. The effects of different operating conditions and configurations on the thermal performance and productivity of the solar system were studied. Results showed that the presence of a humidification-dehumidification system caused an increase in the daily productivity from 28% to 141%.

As well known, the water has a low holdup capability, which decreases the efficacy of the spray tower humidifier. The researchers solved this problem via using the different types of packing materials fixed inside the humidifier to make the holdup capability and the air specific humidity high as much as possible. Packing materials help to make the exposed contact area between water and air large as much as possible with a big contact time. The choice of a packing material is determined regarding the parameters of cost, porosity, water absorbent availability and capacity, and pressure drop. The various types of packing materials such as jute cloth [11], pall rings [12], gunny bag and saw dust [13,14], plastic and wooden slates [15], textile material (viscose) [16], honeycomb paper [17], ceramic [18,19], canvas [20], wire screen matrices [21], plastic pad [22], indigenous structure [23], thorn trees [24], wooden shavings [25], cellulose paper [26,27], Sulzer Mellapak 250Y [28], corrugated packing aluminum sheets [29], and Honey-comb papers [30] were used to increase the efficacy of the humidification process of the HDH unit. Bacha et al. [24] simulated the dynamic behavior of HDH distillation process regarding the principals of the solar multiple condensation evaporation cycles. The feed saline water to the HDH unit was heated by solar energy. They used the thorn trees as a packing inside the humidifier to enhance the evaporation process. It was found that the simulation model results agreed with the experimental results, which led to make the developed mathematical model capable of designing and predicting the heat and mass transfer parameters and as well as the output freshwater distillate of the HDH unit.

The effect of integrating a PV system to heat the air entering the humidifier of the HDH unit on the performance of the thermal desalination unit was investigated technically by Giwa et al. [31]. They concluded that the PV-HDH system was more environmentally preferable than the PV-RO system with a percent of 83.6% decline in the impacts of the environmental conditions. Recently, Siddiqui et al. [32] investigated the performance of HDH distillation system operated under different pressures lower than the ambient pressure. It was revealed that the gain output ratio would increase with decreasing the pressure of the humidifier. Additionally, using the waste gas in a plate heat exchanger to warm the air of the closed air-heated HDH unit was investigated analytically [33]. It was observed that the more the decrease in the heat transfer coefficients of the plate heat exchanger, the more the increase in the gain output ratio of the distillation unit. The effects of using different configurations of packing materials on the performance of the thermal HDH distillation system with forced (up, down, and up-down) and natural air circulation were studied experimentally by Kabeel et al. [34]. Experimental results revealed that the unit performance was superior when the air circulation was forced down compared to the other three cases (natural, forced up, and forced up-down air circulation).

On the second hand, the conventional solar still is the simplest technique of all solar distillation systems, which can be used to provide drinkable water for small communities and single houses in the remote and desert places [35]. Because the distillate production of the traditional still is low, the attention of the scientists was excited to find out new configurations and methods to enlarge and optimize the productivity [36,37]. One of these effective modifications was the various types and arrangements of wick materials which were investigated experimentally and theoretically [38]. Providing a wick material reduces the volumetric heat capacity inside the solar still, which increases the distillate production. Moreover, the output distillate of the solar still can be augmented via preheating the feed basin water because raising the makeup water temperature raises the still water-glass temperature difference, and hence the still output freshwater can be increased.

Regarding the literature, almost previous work for the hybrid system of the solar still and HDH desalination unit was theoretical study. Thorn trees material was used only one time as a packing material [24]. The main objective of the present work is integrating and investigating the performance of the hybrid system of the wick solar stills and the HDH desalination unit. In the humidifier, different packing materials (aspen pad and thorn trees) and various water flow rates (1, 2, 3, and 4 kg/min) were investigated to improve the system performance. Besides, the desalination system was tested during the day- and night times. The performances of the HDH unit and the wick solar stills were evaluated and discussed in detail.

The novelty of this study can be summarized as follows:

1. The first time the aspen pad is used as a packing material in HDH unit.
2. The HDH unit is tested at night times.
3. The performance of the wick solar stills with HDH unit is studied experimentally.

## 2. Experimentations

A schematic of the experimental test-rig is illustrated in Fig. 1. The built test-rig comprised three main components namely the humidifier (evaporator), the dehumidifier (condenser), and the tilted-wick solar stills. In addition, the test-rig included some other auxiliary components such as the solar water heater, pumps, PV system, hot water reservoir, and saline water tank. The experimentations were conducted at University of Prince Sattam bin Abdulaziz, Al Kharj, KSA (24° N Latitude and 47° Longitude).