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Experimental and analytical study on productivity augmentation of a novel solar humidification–dehumidification (HDH) system

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HIGHLIGHTS

- A novel HDH system was developed coupled with water heaters and reflector.
- Productivity up to 366% was achieved for the proposed HDH system.
- The accumulated (daily) evaporated mass up to 41 kg m^{-2} was achieved.
- Peak efficiency equal to 0.77 was achieved.
- The estimated cost of the fresh water produced is 0.035 USD/L.

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ABSTRACT

The aim of this study is to investigate analytically and experimentally the effect of using an induced atmospheric air, water heaters, external reflector and weather condition on the performance augmentation of humidification–dehumidification (HDH) system. This novel HDH system is a modified solar still with air blower and condenser used at humidification chamber inlet and outlet respectively and glass cover is positioned horizontally. Experiments were carried out in April 2014 under the climatological conditions of Madinah (latitude: 24° 33′ N, longitude: 39° 36′ 0″ E), Saudi Arabia. Performance of the HDH system is examined with and without water heaters and reflector. The experimental results showed that the daily productivity of the considered HDH system has improved when using both water heaters and reflector. A remarkable increase in productivity by about 210, 312 and 366% on three test days, namely, April 01, April 15 and April 30 respectively is obtained for still configured with two water heaters at 500 W each and a reflector tilted at 20° compared to that without heaters and reflector. The estimated cost of fresh water produced through the considered HDH system is 0.035 USD/L and the peak efficiency is 0.77.

1. Introduction

Freshwater is the most important factor for sustainable development as it is required for drinking, agricultural and industrial applications. With the significant increase of domestic and industrial freshwater usages, an imbalance between supply and demand of freshwater emerges increasingly in Saudi Arabia. The usage of solar energy to conduct seawater desalination is regarded as a promising technology to solve the freshwater shortage issues. This field has therefore received great attention in the past few years. For different kinds of technologies proposed such as solar chimneys, solar stills, humidification–dehumidification distillation, non-membrane processes, membrane processes, the most typical ones are the humidification–dehumidification and solar still desalination technologies [1–5].

Solar still is a simple device which can be used to supply clean potable water in remote and arid areas where conventional energy is not available or costly. Despite low maintenance, wide use and simple fabrication of traditional horizontal and inclined basin type stills, they are not economical due to their lower water production. A number of attempts were made to improve the productivity of solar stills. To improve the radiation absorption capability of the horizontal basin still, dyes [6] and charcoal pieces [7] were added to the basin water. To store excess energy during nocturnal or cloudy time and to increase effective surface area of the basin, different energy storing and wick materials were used in the basin [8–10]. Glass cover tilt was optimized for maximum condensation collection [11]. External collector [12] and solar pond [13–16] were used to preheat water. External reflector plates [17] at different inclination angles were used to increase the radiation incidence on the solar still. Deniz [18] investigated the effect of parameters such as gap distance, slope of cover and cooling of the cover on the performance of the still. Anburaj et al. [19] demonstrated

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Nomenclature

A_c	area of humidification chamber, m^2
AMC	annual maintenance cost
ASV	annual salvage value
ARC	annual running cost
AC	annual cost
AY	annual yield
a	instrument accuracy
CRF	Capital Recovery Factor
$C_{p,w}$	specific heat capacity of cooling water in condenser, $J\ kg^{-1}\ K^{-1}$
E_y	annual energy consumption, kWh
FAC	first annual cost
h_c	convective heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_{fg}	latent heat of vaporization, $J\ kg^{-1}$
$I(t)$	solar flux, $W\ m^{-2}$
i	annual interest rate
$m_{ev,ex}$	experimental evaporated mass inside the still, $kg\ m^{-2}$
$m_{ev,th}$	theoretical evaporated mass inside the still, $kg\ m^{-2}$
m_{con}	condensed mass, $kg\ m^{-2}$
$\dot{m}_w$	mass flow rate of cooling water in condenser, $kg\ s^{-1}$
$\dot{m}_{air}$	mass flow rate of air induced by the blower fan inside still, $kg\ s^{-1}$
n	lifetime of solar still
P_w	partial pressure of vapor at water temperature, Pa
P_g	partial pressure of vapor at glass temperature, Pa
q_{heater}	heat flux of electric heater, $W\ m^{-2}$
P	initial investment of the still
q_{blower}	heat flux of blower fan, $W\ m^{-2}$
q_{ev}	evaporative heat flux, $W\ m^{-2}$
Q_{con}	heat duty of condenser, W
SFF	Sinking Fund Factor
S	salvage value
t	system running time, h
T_w	water temperature, °C
T_g	glass temperature, °C
$T_{w,o}$	water temperature at condenser outlet, °C
$T_{w,i}$	water temperature at condenser inlet, °C
T_i	operating temperature (average of glass and water temperature), °C
u_{air}	air velocity inside the still, ms^{-1}
u	standard uncertainty
$W_{airblower}$	power of air blower, W
W_{heater}	power of heater, W
x_o	absolute humidity ratio of humid air at still exit, $kg\ kg^{-1}$ of dry air
x_i	absolute humidity ratio of humid air at still inlet, $kg\ kg^{-1}$ of dry air
Z	electricity cost per kWh

Greek symbols

η	Efficiency

an optimum 30° inclination for an inclined solar still with rectangular grooves which yielded 3.77 L/day fresh water. Compared to different wick materials, black cotton cloth helps to achieve maximum productivity of 4.21 L/day. The addition of permeable materials and energy absorbing materials also enhance the distillate output to 4.27 L/day. Parabolic trough concentrators and geothermal energy have also been studied as an effective source of heat to drive the desalination plant [20–22]. An external reflector can be a useful and an inexpensive modification to increase the distillate productivity of single-effect stills. Much literature reported an increase in the productivity of solar stills, and among these was using internal and/or external reflectors to boost the solar radiation absorbed by the basin liner [23,24].

Hamed et al. [25] performed analytical and experimental investigations of solar humidification–dehumidification desalination system. They showed that preheating results in high productivity of about 22 L/day and the total unit cost was about 0.0578 USD/L. Li et al. [26] designed a new kind of solar air heater with evacuated tubes for humidification–dehumidification desalination unit. Sharqawy et al. [27] proposed an optimal thermal design for humidification–dehumidification systems. They demonstrated that large sized humidifiers and dehumidifiers increase the gained-output ratio (GAR) whereas increasing the water temperature at the inlet of a humidifier decreases GAR. H. Kang et al. [28] studied the performance of two stage multi-effect desalination system based on humidification–dehumidification process. Nada et al. [29] studied hybrid humidification–dehumidification desalination and air-conditioning system and demonstrated that increasing air mass flow rate and humidity increases refrigeration capacity and fresh water production rate.

Solar still desalination technology has several merits such as simple structure, easy maintenance and installation and a few moving components but low still efficiency are one of the major concerns which need further investigation. Sivakumar and Sundaram [30] presented a review on different techniques to improve solar still efficiency. Regenerative still with jute cloth has an efficiency of 8%, solar still with sand used as a sensible heat storage material has an efficiency of 37.8% compared to the still without heat storage which has an efficiency of 27%, and solar still with black paint coated jute wick has an efficiency of about 45%. Samee et al. [31] studied a single basin solar still, with an average output of 3.15 L/m^2/day. Khalifa [32] analyzed the effect of the cover tilt angle of a simple solar still on its fresh water productivity, and an output of 4–8 L/m^2/day was obtained for some cases. Rajaseenivasan et al. [33] reviewed the current methods for enhancing the productivity of the multi-effect solar still, and investigated that the productivity can reach up to 9 L/m^2/day for a multi-stage evacuated solar still and a multi-basin still-integrated with waste water flow.

The proposed experimental setup is a modified solar still since the construction of this setup is similar to the solar still with a few modifications such as glass cover positioned horizontally with the addition of an air blower and a condenser at the evaporation chamber inlet and outlet respectively. Therefore, the considered test rig is named as solar humidification–dehumidification (HDH) system instead of a solar still. This paper focuses on enhancing the fresh water productivity by using a novel solar humidification–dehumidification (HDH) system coupled with immersion water heaters and external reflector.

2. Experimental test rig and operating principles

In this work, a humidification–dehumidification (HDH) system integrating with immersion water heaters and external reflector has been fabricated and tested at various weather conditions in Madinah, Saudi Arabia. To retain excess heat in HDH system, a black painted absorber has been used at the bottom of the humidification chamber. The schematic and photograph views of the full experimental test rig are shown in Figs. 1 and 2 respectively. It operates on the basic principle of evaporation inside the chamber air gap and condensation through the attached condenser. Experimentation was carried out on three different sunny days, namely, April 01, April 15 and April 30, 2014. The average daily productivity of the HDH system was studied with and without water heaters and external reflector.

The proposed HDH desalination system consists of a horizontal humidification chamber which has a net evaporation area of 1.2 m^2, is made from 1 mm-thick galvanized steel sheet and has a 4 mm-thick glass cover. The height of the walls is 250 mm, 150 mm devoted to the saline water inside the humidification chamber and the remaining 100 mm for the ambient air flow over the warm water surface. The mass of water inside the humidification chamber is 180 kg. The saline