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Performance of basin type stepped solar still enhanced with superior design concepts

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ABSTRACT

It is difficult maintaining a minimum water depth in a conventional basin type solar still, as the required area is quite large. To overcome this difficulty, the R & D community proposed a stepped solar still in an attempt to increase the production per unit area by decreasing the thermal inertia of the water mass, where the area of the basin is minimized via the utilization of small trays. However, stepped solar still is still potential for further enhancement. It is leaned from the literature, that adding internal and external reflectors, absorber materials (fins) and external condensers are considered superior in enhancing the absorption, evaporation and condensation processes of the basin type solar still. Combining these design concepts concurrently with stepped solar still to enhance its performance is still a missing link in the literature. In this study, a previous work of stepped solar still is selected to apply these modifications on it and propose it as a new design. Energy balance model is developed to compare the performance of the stepped solar still before and after modification. The energy balance results are obtained by solving the energy balance equations for various elements: absorber plate, saline water and glass cover of the solar still. Hourly solar radiation and hourly ambient temperature of clear sky day conditions are used as input data in the energy balance model. The hourly performance of the stepped solar still is compared before and after modification under the following evaluation parameters: temperature difference between saline water and glass cover, evaporation/convective/radiative heat transfer coefficients, solar still productivity and solar still efficiency. The results showed that the hourly values of evaluation parameters after modification are always higher of that before modification. This increment is tested statistically to confirm its significance. So, the differences in the mean values of each evaluation parameter before and after modification are tested by statistical paired *t*-test. The test results confirmed that there is a significant difference in the mean values of each evaluation parameter before and after modification. Moreover, the daily productivity of the stepped solar still after modification increased from 6.9 to 8.9 kg/m^2; this represents 29% enhancement compared to before modification. Finally, based on the results of the evaluation parameters and the statistical test, the thermal performance of the proposed stepped solar still is considerably improved through the new modification.

1. Introduction

Distillation is a popular treatment solution throughout the world. Therefore, it is not surprising that many solar distillation systems were developed and improved upon over the past few decades. The main limitation in the distillation method is the utilization of large amounts of conventional energy sources, culminating in environmental pollution. Part of distillation systems are solar stills, which can be thermally powered by a free and clean source of energy. The basin type solar still is a simple device, easy to fabricate, require less maintenance, and cost effective. Despite these advantages, its use is not widespread due to its low productivity. The aim of this section is to highlight the superiority of certain design concepts and shed light on the potential of combining all these design concepts in a new design of basin type stepped solar still.

Numerous researches were carried out for the purpose of enhancing the productivity of the basin type solar still [1] discussed the role of climate, design and operational parameters on the productivity of basin type solar still, and they concluded that the productivity of basin type solar still require more R & D to efficiently optimize the absorption,

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Nomenclatures

A	area, m^2
A_{ec}	area across the entrance from the basin to condenser (m^2)
D	coefficient of diffusion mass transfer of water vapor in air ($= 2.56 \times 10^{-5}\ m^2\ s^{-1}$)
Cp	specific heat, J/kg K
$I(m)$	solar flux on an inclined collector, $W\ m^{-2}$
I_g	global radiation intensity on a horizontal plate, $W\ m^{-2}$
I_d	diffuse radiation intensity on a horizontal plane, $W\ m^{-2}$
h	heat transfer coefficient, W/m^2k
h_{fg}	enthalpy of evaporation at Tw, J/kg
Δt	time interval, s
m	mass, kg
$\dot{m}$	rate of mass flow ($kg\ s^{-1}$)
P	partial pressure, N/m^2
R_v	vapor gas constant ($J\ kg^{-1}\ K^{-1}$)
T	temperature, °C
U	heat loss coefficient from basin and sides to ambient W/m^2K
V	wind velocity m/s
v_c	vapor in condenser chamber
v_e	vapor in basin
x_{ec}	gap crossed by water vapor from basin to condenser (m)

Greeks

ε	emissivity
α	absorptivity
ρ	reflectance
φ	density $kg\ m^{-3}$
τ	transmittance
β	collector surface inclination, degrees
s	Stefan–Boltzmann constant, $W\ m^{-2}\ K^{-1}$
μd	the daily efficiency of the still
ε	the exergy efficiency

Subscripts

a	ambient
b	basin
c	convective
d	diffusion
e	evaporative
g	glass
r	radiative
w	water

evaporation, and condensation processes.

The addition of internal and/or external reflectors is regarded as effective modifications vis-à-vis increasing solar radiation incident upon the basin liner and its productivity. Abdallah et al. [2] proposed the installation of internal reflecting mirrors in a conventional single slope solar still. The area of the basin solar still in this case was $80 \times 80\ cm^2$. They reported the productivity of solar still with and without mirrors were 2.077 L and 1.408 L, respectively. Tanaka and Nakatake [3] conducted a theoretical analysis of the effect of internal and external reflectors on the solar radiation absorbed by a basin liner and the distillate output of a single-slope conventional still at 30°N latitude. They confirmed that the internal and external reflectors can significantly increase the absorbed solar radiation and increase the distillate output by ~48%. Tanaka [4] theoretically analyzed the conventional basin type solar still with a flat plate external bottom reflector extending from the front wall of the still and internal reflectors (two sides and back walls). It was confirmed that the external/internal reflectors are capable of redirecting sunrays towards the basin liner and increase the productivity of the distillate. Khalifa and Ibrahim [5] experimentally investigated the influence of internal/external reflectors inclined at multiple angles (0° (vertical), 10°, 20° and 30°) upon the productivity of conventional basin solar stills during autumn, summer, and winter. It was confirmed that increased inclination angle of the external reflector from the vertical axis to 30° negatively influence the productivity during the summer (June, July and August). Tanaka [6] experimented with a basin type solar still with internal/external reflectors during winter in Kurume, Japan. He posited that a quick modification using internal/external reflectors is capable of increasing the daily distillate output by ~70–100%.

Murugavel and K. Srithar [7] fabricated and tested a basin type double slope solar still with rectangular aluminum fins. The results proved that the still equipped with a cotton cloth is more effective. Also, Murugavel et al. [8] compared the performance of a solar still with a layer of water in the basin with multiple basin spreader materials. The results proved that the still with black light cotton as its spread material was more effective. Srivastava and Agrawal [9] analyzed the performance of a conventional still with/without porous fins. It was confirmed that the former performed better, with its maximum distillate productivity of ~7.5 kg/m^2 during the summer.

The outcome of the addition of an external condenser was analyzed by researchers. A passive solar still with a separate condenser was modeled, and it performance was analyzed by Madhlopa and Johnstone [10]. The results showed that the productivity of the distillate of the modified still is 62% higher compared to the conventional type. The first, second, and third effects contributed 60%, 22%, and 18% of the total distillate yield, respectively.

Abu Qudais et al. [11] analyzed the outcome of utilizing an external active condenser on the efficiency of a conventional solar still. It was confirmed that the efficiency increased by 47% via the utilization of an external condenser in the solar still. E1-Bahi and D. Inan [12] experimented on the influence of adding an external passive condenser to a single-basin-type solar still. They discovered that when the solar still operates with an external condenser, the yield shot up to 70% of that without a condenser, and the amount of produced distilled fresh water increased to up to 7 L/m^2 day. However, it was also surmised that the presence of a separate condenser could enhance the productivity of the distillate, and that the vapor channel should be designed in a more intricate manner to prevent increased vapor diffusing resistance, as pointed out by G. Xiao et al. [13].

The production per unit area can be increased by decreasing the thermal inertia of the water mass, where a stepped solar still is installed in the basin, subsequently resulting in minimized area due to the presence of small trays, as outlined by Velmurugan et al. [14]. Later, Kabeel et al. [15] analyzed experiments pertaining to the performance of two solar stills. Maximum productivity was realized at a tray depth of 5 mm and width of 120 mm, which is ~57.3% higher compared to that of a conventional still. Abdullah [16] analyzed the experimental performance of a single slope passive solar still and stepped active solar still integrated with a solar air-heater collector. The absorber plate of stepped solar still is made up of 5 steps (each of size 0.1 m × 1 m). The daily productivity reached ~3400 and 6300 ml for conventional and stepped solar stills with air heater, respectively. The output of the latter increased by ~85% compared to its conventional counterpart. Omara et al. [17] compared the modified stepped solar still with trays (5 mm depth × 120 mm width) with the conventional solar still. The stepped solar still was modified via the addition of internal reflectors on the vertical side of the steps. The results pointed out that the productivity of the modified stepped solar still with/without internal reflectors