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Performance evaluation of a new stepped solar still under the desert climatic conditions

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ABSTRACT

This paper presents a new stepped solar still proposed to improve the daily productivity of the conventional basin type solar still (CSS). An internal Multi-Tray Evaporator (MTE) was integrated against the still rear-wall to act as an additional evaporation area. The MTE's effect on the still performances has been evaluated through experimental tests under different meteorological conditions in the region of Adrar-Algeria. The still productivity improvement is demonstrated through a comparative study between the proposed solar still and the conventional still. The experimental data show that the productivity of the proposed stepped solar still is higher than that for conventional still by about 47.18–104.73%. It was found that the estimated cost of distilled water and the payback period, for the stepped solar still are 0.01 $/kg and 70 days, respectively. While, for the simple solar still, they are estimated at 0.0145 $/kg and 100 days.

1. Introduction

Freshwater scarcity is a great problem that millions of people in many regions around the world suffer from. Many reasons are behind this scarcity, the most important are growing population, pollution of water resources, weather changes as well as the large water quantities directed for agricultural and industrial uses [1]. In saharian regions, the situation is more and more serious, especially for those living in remote areas where extreme temperatures contribute to raise the need for drinking water. In these areas, water resources are very limited and most of them are deep groundwater, difficult to exploit. Underground water cannot be directly used for drinking because it contains salt, heavy metals and bacteria, as well as arsenic and many other contaminants. Therefore, post treatment of the brackish water is the only way to provide fresh and drinkable water.

As an alternative solution, solar desalination represents an effective way to solve the water problem in these regions where solar energy is available and water resources are limited. Nowadays, solar desalination is increasingly used thanks to its economic benefits as well as for reasons related to environment protection [2,3]. This available energy can be used for extracting salts and impurities from groundwater to get pure and potable water to satisfy human, animals, agriculture requirements and contributes to the local development of these regions. Conventional Solar Stills are small-scale, solar distillation units, used since long time ago for water desalination and purification. Due to their simplicity and passive nature, they are more recommended for arid and saharian regions as an alternative way of providing good water quality for single houses and small communities [4,5].

At present, solar distillation systems cannot compete with modern desalination plants because their daily production is very limited [6,7]. Indeed, this is true for regions where electrical energy and fuel are available. However, saharian regions, solar stills remain the most appropriate solution for providing fresh water and serving small communities as well as the nomads where construction of pipelines or water transport by truck is uneconomical and unreliable [1]. Improving the CSS productivity has been the subject of several theoretical and experimental investigations. This improvement can be done by introducing proper modifications on the still geometry and their operating mode. These modifications can be obtained after a deep understanding of the main phenomena of heat and mass transfer, taking place in the system as well as the main factors affecting the still performance, such as design, operational and atmospheric parameters [8]. Generally, enhancing the CSS productivity can be achieved by enhancing evaporation, condensation, heat storage and by reducing heat losses [9].

Increasing water evaporation rate in the still is one of the most effective ways that have proven its effectiveness in improving CSS performances. It can be done by several ways among them, increasing the basin water temperature, through using wicks, jute cloths, sponges,

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Nomenclature

A	area (m^2)
C	constant
Cp	heat capacity (J/kg °C)
g	acceleration due to gravity (m/s^2)
Gr	Grashof number
h_{cw}	convective heat transfer coefficient (W/m^2 °C)
h_{ew}	evaporative heat transfer coefficient (W/m^2 °C)
h_{fg}	latent heat of evaporation (J/kg)
I_o	solar intensity (W/m^2)
k	thermal conductivity (W/m °C)
L	characteristic length (m)
$\dot{m}_{ew}$	hourly productivity (kg)
n	constant
Nu	Nusselt number
P	partial vapor pressure (N/m^2)
P_r	Prandtl number
T	temperature (°C)

Greek

α	absorptivity
β	thermal expansion coefficient (K^{-1})
ρ	density (kg/m^3)
ε	emissivity
μ	dynamic viscosity ($N\,s/m^2$)

Indices

a	ambient
g	glass
w	water

rubbers, pin-finned wick in the basin liner and also by minimizing water depth in the still, while the still productivity is inversely proportional to the water depth [10,11]. Maintaining a minimum water depth in the still is technically difficult and the best solution to do this is using stepped solar still, well known for its high productivity [12]. In other words, the stepped solar still is one of the most improvement forms of the CSS with the same design and operating principle except that the absorber basin is made-up with a set of water trays. The stepped solar still is used to increase the water evaporation area, maintaining a minimum water depth and decreasing the thermal inertia of the water mass in the solar still at the same time [13]. The effectiveness of the stepped solar still appears also through other features like its reduced air-cavity volume; its basin absorber is more exposed to solar rays and also by its lower thermal loss on its bottom side compared to other solar still designs. Furthermore, it can be converted to an active solar still by recirculating water over the trays (trickling, cascade) for more distillate production [14,15]. Improving the stepped solar still have been the subject of several experimental and theoretical research works. A comprehensive review of different techniques used to improve the stepped solar still performances is provided by Kabeel et al. [13].

Omara et al. [16] studied theoretically and experimentally a basin type, stepped solar still, modified with the addition of internal reflectors at the vertical sides of the steps. The results show that the productivity of the modified stepped solar still with and without internal mirror reflectors is higher than that for CSS by about 75% and 57%, respectively. Likewise, the daily efficiency for modified stepped still with and without internal reflectors is approximately 56% and 53%, respectively.

Abdallah et al. [17] improved the step-wise basin type solar still by installing reflecting mirrors on all interior sides. The experimental data show that the use of internal mirrors improves the still thermal performance up to 180%. The performance of stepped solar still with internal and external reflectors have been investigated by Omara et al. [18]. These reflectors are used to increase solar energy input to the still. The experimental data indicates that an improvement of about 125% than the CSS was obtained using both internal and external (top and bottom) reflectors.

In addition to internal and external reflectors, El-Samadony et al. [19] have integrated an external condenser to the stepped solar still. The study shows that the stepped solar still productivity with the external condenser is about 66% higher than the conventional one. When using the condenser and reflectors together, the still productivity increases to about 165% higher than the conventional still. In the same context, a theoretical analysis was conducted by Ali et al. [20] to study the stepped solar still performance by combining internal/external reflectors, absorber materials with external condenser together into one design. The study shows that the stepped still performance have been improved by about 29% compared to the stepped still without modification.

Sun tracking systems have been also used to improve the stepped solar still thermal performance. Abdallah et al. [17] introduced a sun tracking system to the step-wise solar still. They found that the still thermal performance can be enhanced to about 380% in comparison with the CSS.

Varying the tray dimensions (depth and width) and their effect on the stepped solar still performance was experimentally and theoretically investigated by Kabeel et al. [21]. Their study revealed that the productivity of the stepped still was 57.3% higher than the conventional still for 5 mm depth and 120 mm width of the tray. By adding wick to the vertical sides of the trays, further increase of about 3–5% in the still daily productivity is obtained.

The effect of the tray surface shape on the stepped solar still performance has been studied experimentally by Jagannath and Lalit [22]. In order to optimize the shape of the absorber basin, three configurations were proposed, namely: flat, convex and concave. The comparison shows that the productivity of the stepped still with the convex surface is 56.6% higher than that with the flat configuration. While, for the concave type configuration the still daily productivity is higher by about 29.24% than that of the flat type.

Recently, Abujazar et al. [23] fabricated an inclined stepped solar still (30° to the horizon) with 28 copper trays and 3 mm water depth. The step-wise basin still was designed to increase the effective evaporation area by about 55.6% compared to a flat-basin design. The proposed still was tested under wet tropical conditions. The experimental tests show that the daily productivity of the still is 4.383 kg/m^2 and the maximum daily efficiency is about 58%. The inclined stepped solar still has been theoretically investigated using a cascade forward neural network to study the effect of environmental parameters on the still productivity [24].

Velmurugan et al. [25] used a stepped solar still and a settling tank to purify the textile effluent. Fins, sponge and pebble were used to improve the stepped solar still productivity. The experimental data revealed that the still production increased by about 53%, 65% and 68% when fins, pebble and sponge were used, respectively and separately. While, the maximum increase in stepped solar still productivity was 98% when fins, sponge and pebble were used together.

Abdullah [26] has fabricated a stepped solar still integrated to a cylindrical plastic solar collector for air heating. The hot air passes under the base of the still for bottom heating of the water. The experiment shows that an increase of about 65% in the still productivity can be obtained by using hot air from a solar air-heater. In comparison to the CSS, the experiments show that an increase of about 112% was