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An experimental approach to improve the basin type solar still using an integrated natural circulation loop

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ABSTRACT

In this paper, a new experimental approach is proposed to enhance the performances of the conventional solar still using the natural circulation effect inside the still. The idea consists in generating air flow by a rectangular natural circulation loop appended to the rear side of the still. The proposed still was tested during summer period and the experimental data presented in this paper concerns four typical days. The convective heat transfer coefficient is evaluated and compared with Dunkle's model. The comparison shows that convective heat transfer is considerably improved by the air convection created inside the still. The natural circulation phenomenon in the still is studied and a good agreement between the experimental data and Vijajan's laminar correlation is found. Therefore, natural circulation phenomenon is found to have a good effect on the still performances where the still daily productivity is of 3.72 kg/m^2 and the maximum efficiency is of 45.15%.

1. Introduction

Solar desalination represents the most prominent and economical method especially when used in arid areas where sunshine is abundant and fresh water is scarce [1,2]. It represents an eco-friendly technology which can open up new water sources and contributes efficiently in the sustainable development of countries. Generally, the Conventional Solar Stills (CSS) are selected due to their simplicity and passive nature, no need for hard maintenance or skilled persons, which leads to little operation and maintenance costs. However, the CSS suffer from some drawbacks, which sometimes limit the use of this system for large-scale production [3]. Some of these drawbacks are, large solar collection area requirement, system vulnerability to weather-related damage, less market demand of technology and low interest of the manufacturers [4,5]. The main limitation is the low productivity compared with other desalination processes, where the daily yield from a single slope basin type solar still may vary from 0.5 to 2.5 kg/m^2 where its efficiency is usually about 5–40% [4,6]. Therefore, it is not cost-competitive with alternative methods.

The main factors affecting the still performances are meteorological conditions, design and operational parameters [7]. In fact, the meteorological parameters like solar intensity, wind velocity and ambient temperature cannot be controlled. Therefore, enhancing the still productivity can be achieved by a proper modifications in the still design and its operating parameters [8]. In the last 30 years, several experimental and theoretical investigations have been carried out to improve the CSS productivity by enhancing evaporation, condensation, heat storage and reducing thermal losses [9,10].

Reducing the water mass is always regarded as one of the key techniques to increase the still water temperature. Many articles focus on the investigation of this effect found that the highest outputs and efficiencies occur at lower depths [10,11]. Reflectors and concentrators are also used to increase water temperature at a faster rate by maximizing the amount of absorbed solar radiation [8,9,12]. Compared to the CSS, the daily productivity could be increased by 70–100% during winter days [13] and for the entire year it would average 48% with little enhancement for the summer days [14]. Sun-tracking systems are also used to increase the solar radiation amount. Abdallah et al. [15] introduced a sun tracking system to a fixed single-slope basin-type solar still. They found that the productivity increases by 22%.

Adding absorbing materials like dyes, wicks, glass balls, rubber, gravel, sand and saw dust are used as thermal storage materials in the basin liner. Rajvanshi [16] found that dye solution increases the single slope solar still productivity by 29%. The same improvement has been obtained by Badran [17] when using asphalt. Adding

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Nomenclature

A	flow cross section (m^2)
C	constant
Cp	heat capacity (J/kg °C)
D	flow hydraulic diameter (m)
f	friction factor, dimensionless
g	acceleration due to gravity (m/s^2)
Gr	Grashof number, dimensionless
Gr'	modified Grashof number, dimensionless
Gr_m	modified Grashof number
h_{cw}	convective heat transfer coefficient (W/m^2 °C)
h_{ew}	evaporative heat transfer coefficient (W/m^2 °C)
h_{rw}	radiative heat transfer coefficient (W/m^2 °C)
h_{fg}	latent heat of vaporization (J/kg)
HR	relative humidity (%)
I_o	solar intensity (W/m^2)
k	thermal conductivity (W/m °C)
m_d	hourly productivity (kg)
n	constant
NC	natural circulation
N_G	geometry number
Nu	Nusselt number
P	partial vapor pressure (N/m^2)
Pr	Prandtl number
Q	heat power (W)
T	temperature (°C)
W	mass flowrate (kg/s)

Greek symbol

β	thermal expansion coefficient (k^{-1})
ρ	density (kg/m^3)
μ	dynamic viscosity (Ns/m^2)
ε	emissivity, dimensionless
σ	Stefan–Boltzman constant (5.6697×10^{-8} W/m^2 k^4)
φ	relative humidity (%)

Indices

b	basin
C	col-leg
eff	effective
f	fluid
g	glass
H	hot-leg
i	inner
o	outer
r	relative, reference
s	sink
t	total
w	water

sponges in the basin liner, increases water evaporation due to capillary forces and the water absorption capacity. Velmurugan et al. [18] and Abu-Hijleh and Rababa [19] conducted experiments on a CSS when sponges were used. They found that the productivity was increased in the range of 15.3–27.3%.

Another important parameter that affects the still productivity is the temperature difference between water and glass cover which acts as a driving force of evaporation process. This effect can be enhanced by an external cooling of the glass cover [20–22]. Arunkumar et al. [23] carried out an experimental study in which water flow was used to cool the hemispherical still glass cover. They found that the productivity increases to about 15% and the efficiency was increased to 42%. Cooling the glass cover of a pyramid-shaped solar still using an external fan was investigated experimentally by Taamneh and Taamneh [24]. The results illustrates that the daily productivity was increased up to 25%.

Reducing the pressure inside the still is another way to increase the still productivity [25,26]. In their experimental study, Sriram et al. [27] used a vacuum pump to suck the vapor inside a single basin double slope solar still and to maintain vacuum pressure at 50 mmHg. Consequently, the still productivity was increased by 50.75%. In addition, integrating a separate condenser with the CSS increases the productivity by increasing the temperature difference between the water and the condenser wall and maintains the still at low pressure. It has been found that adding an external condenser increases the productivity by about 70–75% against the CSS [28–30]. Forced air convection inside the still was also used to increase the solar still productivity. This effect has not received enough attention where a few attempts have been addressed [4,31,32]. Ali et al. [33,34], studied the effect of air convection by placing a fan inside the CSS. He found that the still productivity is increased by about 30%. According to Lawrence and Tiwari [1], operation under natural circulation mode has been proven to be more advantageous in terms of simplicity, reliability and cost effectiveness. Fath et al. [28] found that about 75% of the still productivity is contributed through natural circulation with an efficiency increase of 50% in comparison to CSS.

In this work, an experimental attempt is made to improve the conventional single slope basin-type solar still thermal performances using an integrated Natural Circulation Loop (NCL). The air motion in this case is created by the buoyancy forces that evolve from the density gradients induced by the simultaneous effect of temperature and humidity between evaporator and condenser. The solar still was constructed and tested at the Faculty of Science and Applied Sciences, Oum-El-Bouaghi University, Algeria (Latitude: 35°79′N, Longitude 7°40′E). The tests were carried out in the period of June to July 2014 and the experimental data presented in this paper concerns four typical days. The constant C and n in the Nusselt relation were calculated from the experimental data and compared with those of Dunkle's model. The NC phenomenon inside the still has been investigated and the test data are compared with Vijayan's laminar model. The obtained experimental data show that the daily productivity of the proposed still is about 3.72 kg/m^2, the maximum hourly yield is 0.653 kg/m^2 h and the still efficiency can achieves 45.15%. Consequently, significant improvements are achieved in comparison with the CSS when air convection is created inside the still.

2. System design and experimentation

2.1. Solar still description

A schematic description of the proposed solar still is shown in Fig. 1. The still absorber was constructed with a rectangular galvanized plate of 0.35 m^2 (0.5 m × 0.7 m) with 1 mm of thickness and painted with black spray paint to increase the solar absorption. The absorber is encased in an airtight wooden box with a double glazing cover encloses the still surface. The still bottom side is insulated by glass wool of 10 cm thick to reduce the thermal losses. The still interior sidewalls are of 5 cm height and they are coated by white silicone for reflect solar radiation incident onto the saline water and acts as thermal barrier reducing heat losses [35]. The glass cover in the CSS has been replaced by a double glazing horizontal cover of 3 mm thickness for each glass. In fact, a horizontal cover coupled