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Influence of glass cover inclination angle on radiation heat transfer rate within stepped solar still

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HIGHLIGHTS

- Radiation shape factor between hot saline water and glass cover for stepped solar still is estimated.
- Taking radiation shape factor into account is very important at low solar insolation.
- Taking radiation shape factor into account is very important at high glass cover inclination angle.

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ABSTRACT

In the present work, a new theoretical analysis of the radiation heat transfer rate inside a stepped solar still is presented. Radiation shape factor between hot saline water and glass cover for a stepped solar still is computed. The effect of taking the radiation shape factor into consideration is qualitatively and quantitatively determined. The effect of glass cover inclination angle (from 10° to 70°) and solar insolation (from 200 to 1200 W/m^2) on stepped solar still productivity; taking into account the radiation shape factor is investigated. It is found that the influence of the radiation shape factor on the thermal performance predictions is significant. Moreover, the productivity of the solar still is found to be sensitive to the radiation shape particularly at low solar insolation and/or high glass cover inclination angle (i.e. latitude angle of the site) and vice versa. At low solar insolation of 200 W/m^2 and glass cover inclination angle of 70°, the percentage increase in the still productivity, when considering the radiation shape factor, is up to 18.8%. Finally, fair agreement between the present theoretical work and the previous experimental result has been accomplished.

1. Introduction

Reasonable amounts of fresh water can be produced via inexpensive and robust solar still in areas that are exposed to excessive solar radiation and have brackish water. Many works intended to analyse the factors that affect the performance of solar stills [1]. The distillation productivity of a solar still is significantly influenced by ambient temperature, insulation, wind velocity, dust and cloud ambient condition, saline water depth, salt concentration and inlet temperature of water. The efficiency of solar still was improved through the increase in solar radiation, ambient air temperature, wind speed, and water absorptivity [2]. These studies were achieved experimentally and/or theoretically. The experimental results depend on the accuracy of both fabrications of the solar still and good reliable measuring instruments. However, the theoretical results depend on the right simulation of heat and mass transfer governing equations, especially the radiation effect.

A.K Tiwari and G.N Tiwari [3] studied experimentally the effect of water depth on the mass transfer coefficient for hot climatic condition and passive single-slope distillation system. Tsilingiris [4] investigated in the parameters affected the glazing surface temperature of the solar still. This led to the identification and estimation of the errors associated with the measurement of the solar still productivity. Rahbar and Esfahani [5] investigated the ability of a two-dimensional computational fluid dynamic simulation in estimating the hourly yield of a single-slope solar still.

Many investigations were developed for getting empirical relations for heat and mass transfer coefficients to predict the hourly productivity rate for different configurations of solar stills. The first trial was proposed by Dunkle [6]. Dwivedi and Tiwari [7] proposed a trial by Dunkle's model for estimating the internal heat transfer coefficient of single and double slope passive solar still at different climate conditions. Khaoula et al. [8] performed an analysis for both simple and hybrid solar distillers. Their investigations were aimed to evaluate the values of convective and evaporative heat transfer coefficients. Kumar et al. [9] proposed

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a simple empirical relation for the glass cover temperature as a function of both saline water and ambient temperatures in basin type hybrid active solar still. Hongfei et al. [10] introduced numbers of empirical correlations for both heat and mass transfers in basin type solar stills.

Heat transfer rate within the solar still was performed numerically by Chouikh et al. [11] as a natural convection flow in an inclined cavity; with the streamlines and isothermal ones within the cavity, heat and mass transfer coefficients were obtained. Shawaqfeh and Farid [12,13] used the Dunkle model [6] for the evaluation of evaporative, convective and radiative heat transfer coefficients in a single basin solar still. It was found that this model introduced better expectation for their measured evaporation rate. Tsilingiris [14–16] introduced a comparative comparison between the Dunkle model [6] and experimental results for solar stills. Tsilingiris [17] introduced a new theoretical method based on Chilton–Colburn analogy for the expectation of mass transfer in solar distillation systems for wide ranges of Prandtl and Schmidt numbers instead of the old Dunkle's theoretical model [6]. Alvarado-Juárez et al. [18] optimized numerically the performance of the solar still device. It was simulated as a double diffusive heat and mass transfer natural convection within an inclined enclosure.

Many experimental and numerical studies have been done on different configurations of solar stills to reach the optimum design by examining the effect of cover tilt angle as a key parameter [19] (inclination angle from 5° to 85°). Khalifa [20] studied the effect of glass cover inclination angle (from 5° to 60°) on simple solar still productivity in different seasons.

A decent trial for modelling heat transfer within a basin type solar still was introduced by Madhlopa [21]. Two models were investigated; one of them considered the optical view factors for radiative heat transfer inside a conventional solar still type solar still for more correctness in the theoretical calculations. It was found that the productivity of model which considers the optical view factors was slightly overestimated by the observed one. However, an opposite effect was found for the second model. Madhlopa et al. [22] proposed a model that calculates the distribution of solar radiation inside a basin-type solar still with plane reflectors.

From the previous survey, radiation shape factor between saline water and glass cover for a stepped solar still is not considered. Therefore, the present study will focus on a new accurate simulation for stepped solar stills taking into account the radiation shape factor between saline water and glass at different glass cover inclination angles and solar insolation. Actually, it is well established that the optimum glass cover inclination should be equal to the place latitude angle to receive high radiation.

2. Scope, targets, and methodology

The aim of the present work was to obtain the effect of taking radiation shape factor into consideration for different latitude places i.e. glass cover inclination angle. This is to see where radiation shape factor may be ignored and where it must be considered. The scope of work was focused on improving the theoretical predictions of thermal performance by considering the radiation shape factor between saline water and glass cover, which is the main novelty in this paper. Since there is a relation between such radiation shape factor and latitude, which was represented by the glass cover inclination, the present work has a direct impact on the design, sizing and localization of the stepped solar still. An in-house numerical code was developed in FORTRAN, tested and used to carry on the present study.

3. Mathematical model

The energy balance for the stepped solar still, Fig. 1 will be applied for three regions: basin or absorber plate, saline water, and glass cover. The basin plate temperature, saline water temperature, and glass cover temperature can be evaluated at every instant. In the present

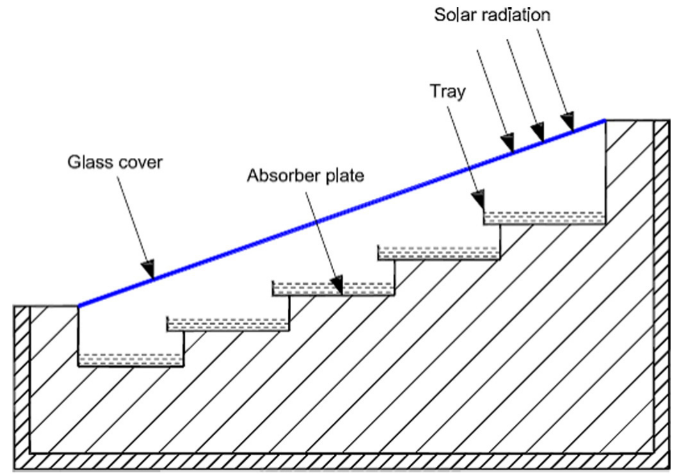

Fig. 1. Stepped solar still.

study, the following assumptions are considered for the solar still energy equations:

- Steady state conditions
- The glass cover is assumed to be thin
- The solar still is vapour leakage proof.

Energy balance for the basin plate [23],

$$m_{bp}Cp_{bp}\frac{dt_{bp}}{d\tau} = (\alpha_{bp})A_{bp}I - Q_{b-sw} - Q_{lost}. \tag{1}$$

Energy balance for the hot saline water [26],

$$m_{sw}Cp_{sw}\frac{dt_{sw}}{d\tau} = (\alpha_{sw})A_{sw}I + Q_{b-sw} - Q_{r(sw-g)} - Q_{c(sw-g)} - Q_{evap} - Q_{mw}. \tag{2}$$

Energy balances for the glass cover [24],

$$m_gCp_g\frac{dt_g}{d\tau} = (\alpha_g)A_gI + Q_{r(sw-g)} + Q_{c(sw-g)} + Q_{evap} - Q_{c(g-a)} - Q_{r(g-a)}. \tag{3}$$

The convective heat transfer between basin plate (absorber) and saline water, Q_{b-sw}, may be obtained as follows [25,26]

$$Q_{b-sw} = h_{b-sw}\,A_{bp}(t_{bp} - t_{sw}) \tag{4}$$

The convective heat transfer coefficient between basin and water, h_{b-sw} is taken as 135 W/m^{2}K [25,26].

The heat losses by convection through the basin base and sides to the ground and surrounding, Q_{lost} given as [27]

$$Q_{lost} = U_{bp}\,A_{bp}(t_{bp} - t_a) \tag{5}$$

where U_{bp} (14 W/m^2 K) is the heat loss coefficient from basin plate and to ambient.

Table 1
Physical and operating parameters used in the theoretical calculation.

Item	Mass (kg)	Area (m^2)	Specific heat (J/kg K)	Absorptivity	Emissivity
Saline water	5.9	1.00	4190	0.05	0.96
Glass cover	9.0	[a]	840	0.05	0.85
Basin plate	14.5	1.00	460	0.95	–

[a] This parameter is calculate based on the glass cover inclination angle.