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Glass cover inclination angle effect on the radiation shape factor within conventional solar still

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ABSTRACT

In the present work, a new theoretical study of the effect of considered shape factor between hot saline water and glass cover in a conventional solar still is investigated. The radiation shape factor is calculated. Solar still productivity when taking the radiation shape factor into consideration is obtained and then compared with when it is not considered. The effects of glass cover inclination angle and solar insolation on solar still productivity when taking shape factor into account is obtained and correlated. It is found that taking radiation shape factor into account gives more accurate results than ignoring it. The deviation between the two results is highly depended on the inclination angle and solar insolation. At low solar insolation of 200 W/m^2 and glass cover inclination angle of 70˚, the percentage of the increase in still productivity when taking radiation shape factor into account is arrived to 22.3%. Finally, a good agreement between the present theoretical work and previous experimental result has been obtained.

Keywords: Conventional solar still; Distillation; Shape factor; Theoretical

1. Introduction

Solar distillation of sea water is, without doubt, one of the rare possibilities to satisfy the water needs in numerous regions of the world in a sustainable way. Numerous studies were achieved to simulate both heat and mass transfer within the solar stills with both numerical and experimental approach.

Ahsan and Fukuhara [1] introduced a new double-diffusive (mass and heat transfer) model of a tubular solar still. The model took into account the humid air properties inside the still. The model was validated by experimental work and good agreement was found. Boubekri et al. [2] simulated solar active still with a single basin liner and a single slope fitted with two reflectors coupled with a photovoltaic/thermal solar water heater system. The simulation was performed year around for the still productivity. Chen et al. [3] performed an attempt to simulate principles of heat and mass transfer as well as the parameters of water production by desalination. The simulation was performed by residual heat-powered three-effect tubular solar still. The energy balance within the still includes natural convection mass transfer and radiation heat exchange. El-Agouz et al. [4] performed mathematical model for three solar water desalination models;

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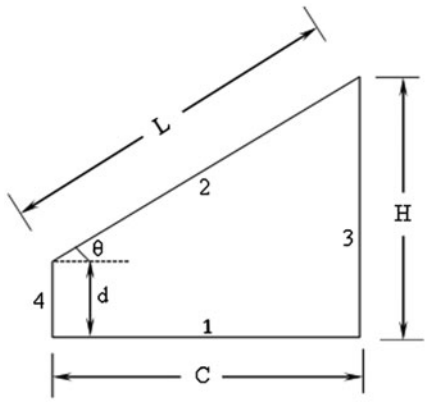

Fig. 1. Conventional solar still.

inclined solar still desalination system with and without water closed-loop unit and conventional solar still. They found that the inclined solar still with a makeup water is superior in productivity (57.2% improvement) compared with a conventional basin-type solar still. Dwivedi and Tiwari [5] evaluated the heat transfer coefficient of single- and double-slope passive solar stills for different climate conditions. Also, they compared the experimental results by the theoretical study based on Dunkle's model [6], good agreement was found. Hamadou and Abdellatif [7] performed a model for simulation for a single-slope solar still. This model included all parameters for the solar still production rate; optimization for the productivity was performed. Jareanjit et al. [8] developed a mathematical model not for water desalination, but for a modified brewery tank for producing fuel ethanol. The model explained that the differences between predicted and experimental results were due to errors in the heat transfer rate prediction of the model. Kumar et al. [9] developed a simple empirical relation for glass cover temperature in basin-type hybrid (PV/T) active solar still at different water and ambient temperatures. Maalem et al. [10] proposed a model of heat and mass transfer calculations for a trapezoidal-shaped solar distiller. The obtained equations were in good agreement with those obtained experimentally. New model for the radiative heat transfer inside a basin-type solar still was introduced by Madhlopa [11]. He took into account the optical view factor between the saline water and glass cover. He obtained a good accuracy for the productivity rate of the still. Madhlopa and Clarke [12] investigated on the irradiation inside a basin-type solar still. They took into account the surface finish, view factors and multiple reflections to get a high degree of accuracy for irradiance distribution prediction inside the still. Martinek and Weimer [13] performed a modelling for radiation heat transfer within closed-cavity solar receivers. They compared the finite volume method with Monte Carlo techniques. Santos et al. [14] performed simulation using artificial neural networks for the determination of the performance of solar still. The obtained results showed that the artificial neural networks could be used for expectation of the performance of different solar still designs. Setoodeh et al. [15] introduced a model with computational fluid dynamic to perform the processes of evaporation and condensation in solar still. The gained numerical results were verified by the experimental data. Kabeel et al. [16] studied experimentally the performance of a conventional still and a modified still uses a rotating fan working by a small photovoltaic (PV) system. They found that using rotating fan in the solar still increases the productivity by 25%. Alvarado-Juárez et al. [17] studied numerically solar still double-diffusive natural convection and surface thermal radiation in an inclined cavity. They found that surface thermal radiation modifies the fluid flow from one-cell to multi-cellular pattern, as a result the average convective Nusselt number, the total Nusselt number and the Sherwood number were increased by about 25, 175 and 15%, respectively. Tsilingiris [18,19] performed an investigation for the accuracy of Dunkle's model [6] in compare with Chilton–Colburn analogy model, the study was aimed to determine the applicable ranges for these models. Tsilingiris [20] presented an analysis for the effect of binary mixture thermo physical properties in the solar still on the transport evaporation and condensation processes and also the associated productivity. Omara et al. [21] studied experimentally the effect using internal reflectors on the performance of stepped solar still. Also, they compared between the still productivity for conventional, stepped and stepped with internal reflectors.

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 parameters, Nafey et al. [22] (inclination angle from 5° to 70°) and Aybar and Assefi [23] (inclination angle from 5° to 85°). Khalifa [24] studied the effect of glass cover inclination angle (from 5° to 60°) on simple solar still productivity in different seasons and latitude angles. He found that the optimum glass cover inclination angle should be closed to the latitude angle of the site.

In the authors' opinion, all the investigated researches in numerical approach considered the energy balance equations within the still not included the radiation shape factor for radiation between saline water and glass cover. The only one was performed

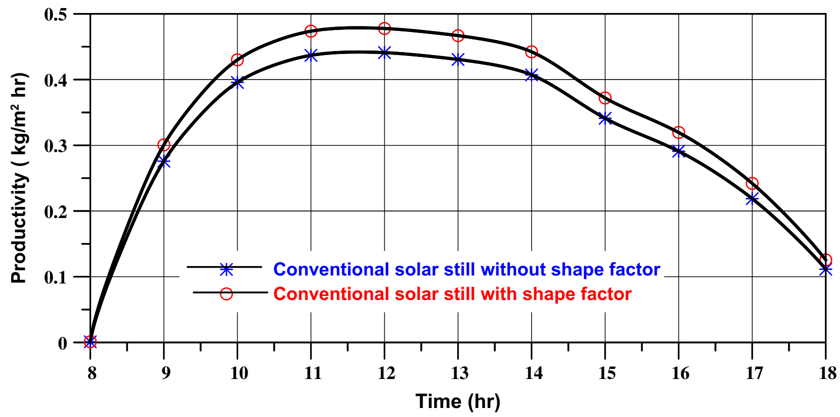

Fig. 2. Productivity for conventional solar still.

by Madhlopa [11], but only for conventional solar still for a single-glass cover inclination angle. The present study concerns with the study of the solar still performance, taking into account the radiation shape factor for radiation heat transfer between saline water and glass cover for different glass cover inclination angle and solar insolation. Actually, it is well established that the optimum glass cover inclination should equal to the latitude of place to receive more radiation. The aim of the present work to obtain the effect of taking radiation shape factor into consideration for different latitude places i.e. glass cover inclination. This is to see where radiation shape factor may be ignored and where it must be considered.

2. Mathematical model

In the present model Fig. 1, energy balance for the conventional solar still will be applied on basin or absorber plate, hot saline water and glass cover. The temperature of basin plate, saline water and glass cover can be evaluated at every instant. In the present study, it is assumed steady-state conditions, glass cover is assumed to be thin and solar still is vapour leakage proof.

Energy balance for the basin plate [25]:

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

The convective heat transfer between basin and water, Q_{b-sw}, may obtained as follow [26,27]:

$$Q_{b-sw} = h_{b-sw} A_{bp} (t_{bp} - t_{sw}) \tag{2}$$

The convective heat transfer coefficient between basin and water, h_{b-sw} is given by [26]:

$$h_{b-sw} = 0.54 \frac{K_{sw}}{X} [\mathrm{Gr}\,\mathrm{Pr}]^{0.25} \tag{3}$$

$$\mathrm{Gr} = \left[\frac{\rho_{sw}^2 g \beta_{sw} (T_{bp} - Ts_w) [X]^3}{\mu_{sw}^2} \right] \tag{4}$$

$$\mathrm{Pr} = \left[\frac{C_p \mu}{K} \right]_{sw}$$

The heat losses by convection through the basin base and sides to the ground and surrounding, Q_{lost}, given as [28]:

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

where U_{bp} (20 W/m^2 K) is the heat loss coefficient from basin plate and to ambient.

Energy balance for the saline water [25,29]:

$$m_{sw} Cp_{sw} \frac{dt_{sw}}{d\tau} = (\alpha_{sw}) A_{sw} I + Q_{b-sw} - Q_{wg} - Q_{c(sw-g)} - Q_{evap} - Q_{mw} \tag{6}$$

The convective heat transfer between saline water and the glass cover, $Q_{c(sw-g)}$, is given by [26,27]:

$$Q_{c(sw-g)} = h_{c(sw-g)} A_{sw} (t_{sw} - t_g) \tag{7}$$

The convective heat transfer coefficient between saline water and glass cover, $h_{c(sw-g)}$, is given by [30]:

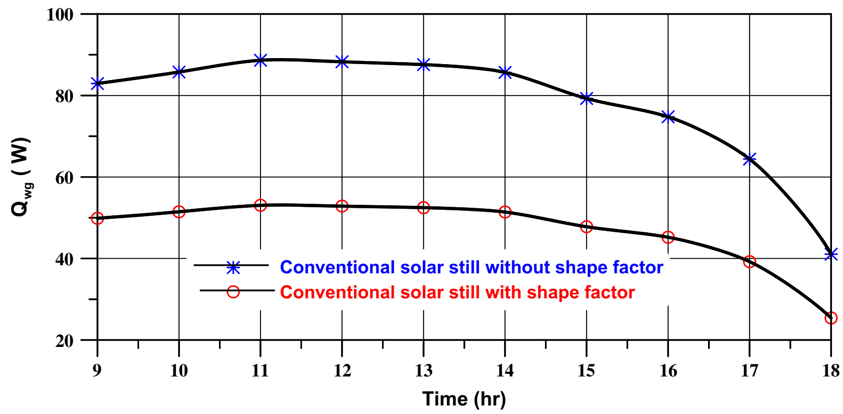

Fig. 3. Radiation heat transfer between water and glass for conventional solar still.

$$h_{c(sw-g)} = 0.884\left[t_{sw} - t_g + \frac{(p_{sw} - p_g)(t_{sw} + 273)}{268900 - p_{sw}}\right]^{1/3} \quad (8)$$

where $p_{sw} = e^{\left(25.317 - \frac{5144}{t_{sw}+273}\right)}$ (9)

$$p_g = e^{\left(25.317 - \frac{5144}{t_g+273}\right)} \quad (10)$$

The radiation heat transfer from the basin to glass cover, Q_{wg}, is given by:

$$Q_{wg} = \frac{\sigma\left[(t_{sw} + 273)^4 - (t_g + 273)^4\right]}{\left(\frac{1-\varepsilon_w}{A_{sw}\varepsilon_{sw}}\right) + \left(\frac{1}{A_g F_{gw}}\right) + \left(\frac{1-\varepsilon_g}{A_g \varepsilon_g}\right)} \quad (11)$$

The radiation shape factor between the glass cover and saline water for the conventional solar still may be calculated as follow:

For any two perpendicular surfaces with common edge, the radiation shape factor will be [31]:

$$F_{1-2} = \frac{1}{\pi\phi}\left[\left[\phi \tan^{-1}\frac{1}{\phi} + J \tan^{-1}\frac{1}{J} - \sqrt{\beta}\tan^{-1}\frac{1}{\sqrt{\beta}}\right] + \frac{1}{4}\ln\left\{\left[\frac{\psi\gamma}{\beta+1}\right]\left[\frac{\phi^2(1+\beta)}{\psi\beta}\right]^{K^2}\left[\frac{J^2(1+\beta)}{\psi\beta}\right]^{J^2}\right\}\right] \quad (12)$$

where $J = s_3/s_2, \phi = s_1/s_2, \quad \beta = J^2 + \phi^2, \quad \psi = 1 + \phi^2$ and $\gamma = 1 + J^2$.

Radiation shape factor between the glass (surface 2) and saline water (surface 1) for the conventional solar still, F_{wg} or F_{1-2} as follow [31] Fig. 1:

$$F_{wg} = F_{1-2} = 1 - [F_{1-3} + F_{1-4} + 2F_{1-0}] \quad (13)$$

$$F_{gw} = (A_w F_{wg})/A_g \quad (14)$$

The values of F_{1-3} (radiation shape factor between saline water (surface 1) and vertical height H (surface 3)), F_{1-4} (radiation shape factor between saline water (surface 1) and vertical height D (surface 4)) and F_{1-0} (radiation shape factor between saline water (surface 1) and the vertical side walls (surface 0)) may be obtained by substituting in Eq. (12) by the values of both J and K as listed in Table 1 where:

$$H = L\sin\theta + d \quad \text{and} \quad C = L\cos\theta \quad (15)$$

The evaporative heat transfer between saline water and the glass is given by [26,27]:

$$Q_{evap} = (16.237 \times 10^{-3})h_{c(sw-g)}A_{sw}(p_{sw} - p_g) \quad (16)$$

The energy needed to heat the makeup water, Q_{mw}, is given as follows:

$$Q_{mw} = m_{prod}(Cp_{sw}t_{sw} - Cp_a t_a) \quad (17)$$

Energy balance for the glass cover [25,32]:

$$m_g Cp_g \frac{dt_g}{d\tau} = (\alpha_g)A_g I + Q_{wg} + Q_{c(sw-g)} + Q_{evap} - Q_{c(g-a)} - Q_{r(g-a)} \quad (18)$$

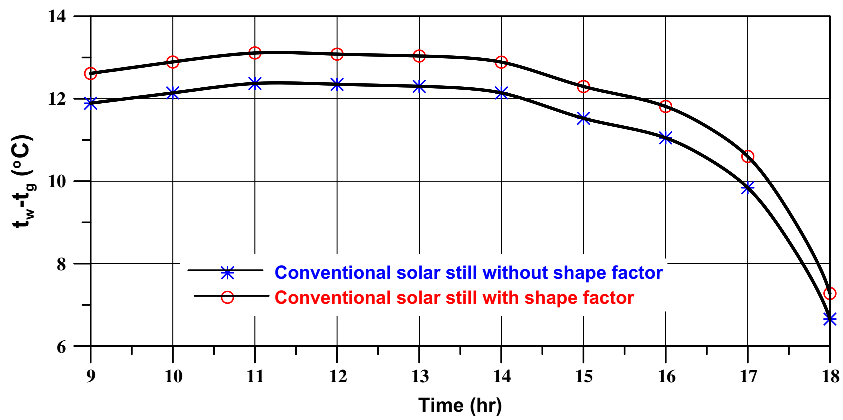

Fig. 4. Water glass temperature difference for conventional solar still.

The radiative heat transfer between the glass and the sky is given by [26,27]:

$$Q_{r(g-a)} = \varepsilon_g A_g \sigma \left[(t_g + 273)^4 - (t_{sky} + 273)^4 \right] \tag{19}$$

The sky temperature is given by [27]:

$$t_{sky} = t_a - 6.0 \tag{20}$$

The convective heat transfer between the glass and the sky is given by [30]:

$$Q_{c(g-a)} = h_{c(g-a)} A_g (t_g - t_{sky}) \tag{21}$$

$$h_{c(g-a)} = 5.7 + 3.8\, V_a \tag{22}$$

Solar still productivity:

$$m_{prod} = \frac{Q_{evap}}{h_{fg}} \tag{23}$$

The percentage distillate productivity of the solar still with the calculated radiation shape factor to distillate productivity of the solar still without calculating radiation shape factor is as follow:

$$\% = \frac{(m_{prod})_{with} - (m_{prod})_{without}}{(m_{prod})_{without}} \times 100 \tag{24}$$

At the first iteration, the temperatures of basin plate, saline water and glass cover are taken as ambient temperature and the increase in basin temperature (dt_b), saline water temperature (dt_w) and glass temperature (dt_g) are computed by solving the energy Eqs. (1), (6) and (18). The equations are evaluated numerically using the first-order backward difference formula [33]. The size of the time step is one second. The value of the heat loss coefficient from basin to ambient for the solar still were taken as that of [34]. In the next time step, the parameters are redefined as follows:

$$t_{sw} = t_{sw} + dt_{sw} \tag{25}$$

$$t_g = t_g + dt_g \tag{26}$$

$$t_{bp} = t_{bp} + dt_{bp} \tag{27}$$

To be very close to real ambient conditions, the theoretical values of the solar insolation and ambient temperature are not used. The actual insolation (I) and ambient temperature (t_a) are measured at different days from 9 am to 6 pm during the period of June–August 2014 at the Faculty of Engineering, Tanta city, Egypt, and the average values of insolation and ambient temperature are used. The physical and operating parameters that used in the theoretical calculations are shown in Table 2.

3. Results and discussion

A detailed study of the effect of taking radiation shape factor between the glass cover and saline water into consideration for the conventional solar still has been investigated. Moreover, the effect of glass cover inclination angle when taking radiation shape factor into consideration on conventional solar still productivity is studied. To show the effect of these parameters on the distillate productivity and radiation heat transfer inside the still individually, a FORTRAN

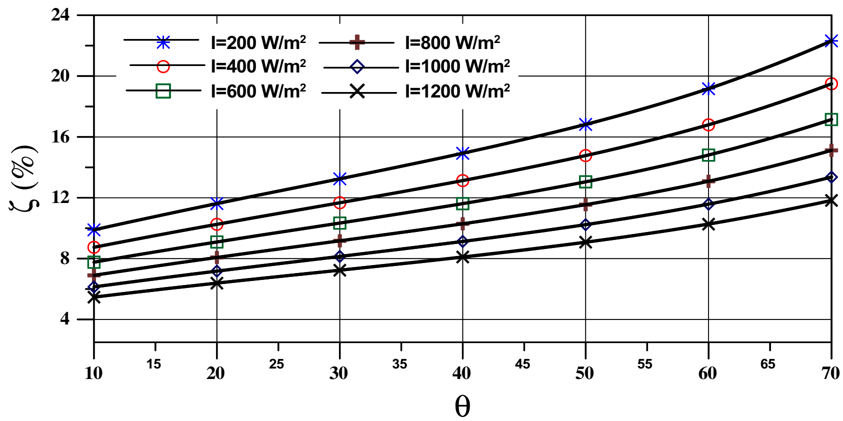

Fig. 5. Glass cover inclination angle, θ, to the percentage of ζ for different insolation (I).

computer program is designed. Fig. 2 shows the variation of the hourly solar still distillate productivity to day time for conventional solar still when radiation shape factor is considered and when it is not considered. It could be seen from this figure that over the entire range of insolation day time, the distillate productivity of the solar still with calculated radiation shape factor is greater than that for still without radiation shape factor. The distillate productivity of the solar still with the calculated radiation shape factor is increased by about 9.0–12.6% than that for solar still with ignored radiation shape factor. This is because when taking radiation shape factor into account radiation heat transfer thermal resistance between the saline water and glass cover will be increased and consequently, the rate radiation heat transfer will be decreased as shown in Fig. 3. Therefore, saline water temperature will be increased, as shown in Fig. 4, which increases the distillate productivity.

To see the effect of taking radiation shape factor into consideration for different latitude places i.e. different glass cover inclination angle, and the effect of the place solar insolation or solar insolation at a certain time, Fig. 5 shows the variation of the glass cover inclination angle, θ, to the percentage of increase in daily solar still distillate productivity due to taking radiation shape factor into account, ζ, for different solar insolation (I). It could be seen from this figure that as glass cover inclination angle, θ, increases ζ increases and this superior is increased as insolation (I) decreased. This is because as the glass cover inclination angle increases, radiation shape factor between saline water and glass cover decreases. It could be noted also from Fig. 5 that, at low solar insolation of 200 W/m^2, the percentage of increase in daily still distillate productivity due to taking radiation shape factor into account, ζ, is over 16% when glass cover inclination angle greater than 45˚. It is important to

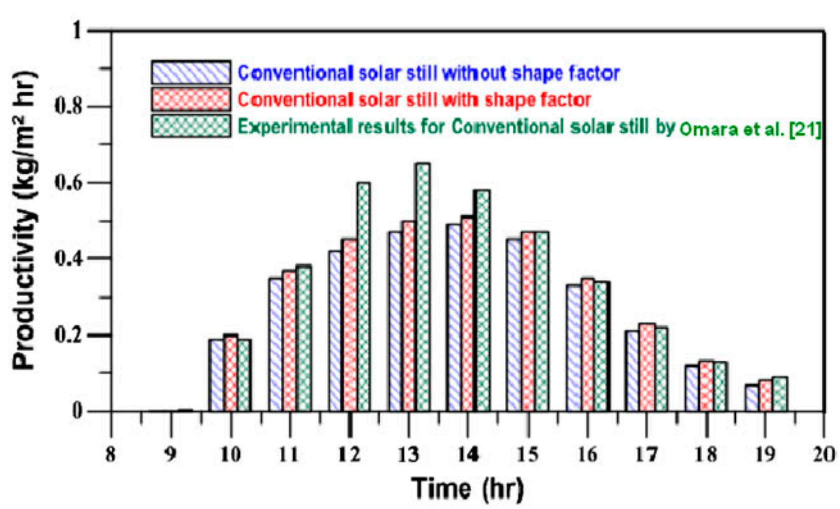

Fig. 6. Comparison between the present work and Omara et al. [21] output results.

Table 1
The values of both J and ϕ for different surfaces in the conventional still

	F_{1-3}	F_{1-4}	F_{1-0}
J	$\frac{H}{W}$	$\frac{d}{W}$	$\frac{H+d}{2C}$
ϕ	$\frac{C}{W}$	$\frac{C}{W}$	$\frac{W}{C}$

note that the recommended glass cover inclination angle is highly related to city latitude angle and hence solar insolation and ambient temperature.

4. Present work validation

To verify the present theoretical work, the experimental results of Omara et al. [21] are used. All Omara et al. [21] insolation (I) and ambient temperatures (t_a) working conditions are fed to the present work program. Fig. 6 compares the present work with Omara et al. [21] output results for hourly productivity of solar still (without internal reflectors). It could be seen from this figure that the value of distillate productivity when taking radiation shape factor into account is very close to Omara et al. [21] experimental results than that when ignored the radiation shape factor. This indicates that ignoring radiation shape factor underestimates distillate output due to overestimation of the radiative heat transferred from the saline water to the glass cover.

5. Correlation of the results

The theoretical values of the percentage of increase in daily solar still distillate productivity (ζ) due to considering radiation shape factor over the range of the investigated inclination angle, (θ) (10–70°) and insolation (I), (200–1,200 W/m^2) values are correlated as follows:

$$\zeta = 9.008 + 0.194\,\theta + 1.465 \times 10^{-9}\theta^5 + 8.652 \times 10^{-8}\theta I^2 - 0.004\,I - 0.00016\,\theta I - 5.07 \times 10^{-10}\,I^2\theta^2 \quad (28)$$

The maximum deviation for the correlation is within 3% which is more applicable than the theoretical values.

Table 2
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	4,190	0.05	0.96
Glass cover	9.0	1.15	840	0.05	0.85
Basin plate	14.5	1.00	460	0.95	–

Note: Latent heat (h_{fg}) = 2,335,000 J/kg.

6. Conclusions

The performance evaluation of a conventional still was theoretically investigated. The effect of considering radiation shape factor between hot saline water and glass cover film into consideration on the productivity of solar still was studied numerically. From the analysis, the following conclusions can be drawn.

(1) Radiation shape factor between hot saline water and glass cover for solar still is calculated.
(2) Taking radiation shape factor into account gives more accurate still productivity than ignoring it.
(3) Taking radiation shape factor into account is very important at low solar insolation or high glass cover inclination angle. (i.e. when solar still located in a city at high latitude) and vice versa.
(4) A good agreement between the present theoretical work and previous experimental is obtained.
(5) An acceptable correlation for the percentage of rise in daily solar still distillate productivity due to considering radiation shape factor over the range of the investigated inclination angle and insolation values is obtained

Nomenclature

A — area (m^2)
a — step height (m)
b — step length (m)
Cp — heat capacity (J/kg°C)
F — radiation shape factor
F_{i-0} — shape factor between surface i and the two vertical side walls of the still
h_{b-sw} — convection heat transfer coefficient between the basin and saline water (W/m^2°C)
$h_{c(g-a)}$ — convection heat transfer coefficient with the ambient (W/m^2°C)

$h_{c(sw-g)}$	—	convection heat transfer coefficient between the water in basin and glass (W/m^2°C)
h_{fg}	—	latent heat of vaporization (J/kg)
I	—	solar insolation normal to glass cover (W/m^2)
L	—	length of glass cover (m)
m	—	mass (kg)
m_{prod}	—	rate of mass evaporation (kg/s)
P_g	—	water vapour pressure at glass temperature (Pa)
P_{sw}	—	water vapour pressure at water temperature (Pa)
Q_{b-sw}	—	heat transfer from basin to water in basin (W)
$Q_{c(g-a)}$	—	heat transfer from glass to ambient (W)
$Q_{c(sw-g)}$	—	heat transfer from water in basin to glass (W)
Q_{evap}	—	heat transfer due to evaporation (W)
Q_{lost}	—	heat transfer from basin to ambient (W)
Q_{mw}	—	energy needed to heat makeup water to water basin temperature (W)
$Q_{r(g-a)}$	—	radiation heat transfer from glass to ambient (W)
Q_{w-g}	—	radiation heat transfer between water in basin to glass (W)
S_1	—	horizontal surface edge length (m)
S_2	—	perpendicular surfaces common edge length (m)
S_3	—	vertical surface edge length (m)
t	—	temperature (°C)
V_a	—	wind velocity (m/s)
W	—	width of the solar still (m)
U	—	heat loss coefficient from basin and sides to ambient (W/m^2 K)

Greek letters

α	—	absorption coefficient
ε	—	emissivity coefficient
μ	—	dynamic viscosity (kg/m s)
τ	—	time (s)
ρ	—	density (kg/m^3)
X'	—	characteristic length (m)
σ	—	Stefan–Boltzmann constant (W/m^2 K^4)

Subscripts

1, 2, 3, 4	—	surface number
a	—	ambient
bp	—	basin plate
g	—	glass
sky	—	sky
sw	—	saline water in basin

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