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A mathematical model of single basin solar still with an external reflector

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ABSTRACT

A transient mathematical model was presented for a single basin solar still with and without an external reflector. The model was based on an analytical solution of the energy balance equations for various elements of the still. The performance of the still with and without the external mirror was investigated by computer simulation using the climatic conditions of Jeddah (lat. 21° 42′ N, long. 39° 11′ E), Saudi Arabia. Effects of solar radiation intensity and mass of basin water on the daily productivity P_d and efficiency η_d of the still were studied. On typical summer (17/7/06) and winter (17/1/06) d, values of P_d of 10.563 and 6.650 (kg/m^{2}d) with daily efficiencies of 56.78 and 52.04% were obtained with mirror compared to 4.605 and 2.260 (kg/m^{2}d) with daily efficiencies of 50.69 and 44.76% when the still is used without mirror. To validate the proposed mathematical model, the simulated results were compared with the measurements that had been performed for the still under Tanta, lat. 30° 47′ N (Egypt), weather conditions. It was found that the proposed model is able to predict the daily productivity and efficiency of the still with a reasonable accuracy. Furthermore, the proposed model was used to predict the annual performance of the still with and without mirror. The annual average of P_d with mirror is found to be 52.75% higher than that when the still is used without mirror.

Keywords: Solar stills; Single basin; External reflector; Productivity

1. Introduction

There is an urgent need for clean, pure drinking water in many countries. Often, water sources are brackish and/or containing harmful bacteria and therefore can not be used for drinking. In addition, there are many coastal locations where sea water is abundant but potable water is not available. Pure water is also needed in some industries, hospitals and schools. Solar distillation is one of many processes that can be used for water purification. Solar radiation can be the source of heat energy where brackish or sea water is evaporated and is then condensed as pure water.

Solar stills are broadly divided into passive and active stills. In a passive solar still, the solar radiation transmitted through the glass cover and basin water is absorbed by the basin liner; hence, its temperature increases. Part of thermal energy is transferred by convection to the basin water and the other will be transferred by conduction to the ground. The basin water transfers heat to the inner surface of the glass cover by radiation, convection and evaporation. The heat is conducted through the cover and then transfers to surroundings by radiation to the sky and by convection to ambient air. Extensive research was reported on different methods that had been used to improve the productivity of these stills [1–4]. An attempt had been made by Tiwari et al. [5] to review work on solar distillation systems.

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The important parameters affecting the performance of a solar still, such as solar intensity and the mass of basin water [6] as well as wind speed [7], were also reported. Still performance was found to increase with thinner water films. However, decreasing the thickness of basin water results in a decrease of overnight productivity of the still [8]. Therefore, to enhance the still productivity during the night even with thinner water films, the concept of using phase change materials as storage media under the basin liner was recently proposed by El-Sebaii et al. [9]. Also, a new design of a passive solar still with separate condenser was modeled, evaluated and compared with that of a conventional still under the same climatic conditions [10]. The system has one basin in the evaporation chamber and two other basins in the condensation chamber. The results showed that the distillate productivity of the new still is 62% higher than that of the conventional type. Tiwari et al. [4] outlined that the passive solar distillation is a slow process for the purification of brackish water because in a passive solar still, the solar radiation is received directly by the basin water and is the only source of energy for raising the water temperature and consequently, the evaporation leading to a lower productivity. The productivity of the passive solar stills can be improved through active methods (active stills) by integrating the still with a solar heater, solar concentrator, solar pond, waste hot water or other heating devices. Therefore, many attempts were made to improve the performance of passive solar stills by coupling these stills to flat plate collectors [11], shallow solar ponds [12,13] and solar concentrators [14]. All these methods introduce additional costs and some difficulty in operation and maintenance of active solar stills. Another method that may be used to improve the productivity of active and passive solar stills is by using external and/or internal reflectors to increase the amount of solar radiation intensity available to the still for water evaporation. Therefore, many attempts had been carried out to improve the productivity of solar stills using an external acrylic mirror [15], external parabolic [16] or concave [17] reflectors and also using internal reflectors [18]. It was concluded that the increase in efficiency and aperture area of the reflector increases the productivity [16]. Also, the thermal performance of a step-wise basin solar still had been improved by 30% on using an internal mirror [18].

Furthermore, theoretical analysis of a basin type solar still with an internal reflector and with internal and external reflectors was carried out by Tanaka and Nakatake [19–21]. Numerical analysis to investigate the effect of vertical [22] and inclined [23] flat plate external reflectors on productivity of tilted wick solar stills was also recently performed by the same authors. They proposed a complicated but a straightforward geometrical method to calculate the solar radiation reflected by the internal and/or external reflectors and then absorbed on the basin liner. They outlined that the daily productivity of the still with the inclined external reflector is 16% greater than that with the vertical external reflector and about 2.3 times as large as that of the still with neither the internal nor the external reflector on a winter day [19]. Also, the external reflector increased the productivity of the wick-type solar still by 9% during the summer season [22]. It is clear that the external and/or internal reflectors improve the productivity of solar stills. However, a disadvantage of using the internal mirrors is the rapid spoiling of the used mirrors by water vapor.

This paper presents a transient mathematical model to simulate the performance of a single basin solar still integrated with an external reflector hinged on the short side of the still cover. The amount of solar radiation reflected from the mirror was calculated using a simple method [24]. Numerical calculations had been carried out for typical summer and winter days for Jeddah (Saudi Arabia). To verify the proposed theoretical model, comparison between measured and calculated results was performed and some conclusions were drawn.

2. Thermal analysis

A schematic diagram of the conventional single basin solar still is shown in Fig. 1a. The basin area of the still is 1 m^2; fabricated from a black painted galvanized iron sheet of thickness 2 mm. The bottom and sides of the basin are insulated by 3 cm layer of sawdust contained in a wooden frame of 1 cm thickness. The cover of the still is made up of 3 mm thick soda glass, making an angle of 21.76° with horizontal that equals to the latitude of Jeddah (21.76° N). The fresh water is collected in an aluminum channel fixed at the lower end of the glass cover. To increase the amount of solar radiation

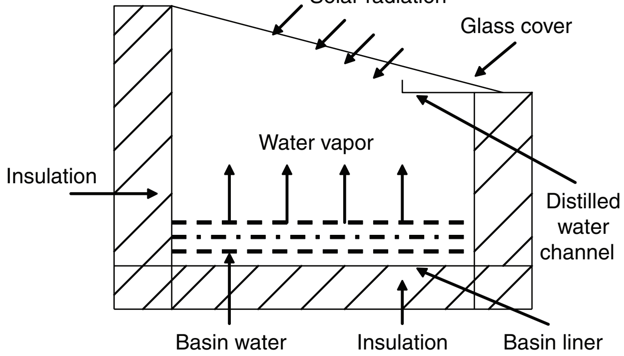

Fig. 1a. A schematic diagram of the single basin solar still without the external mirror.

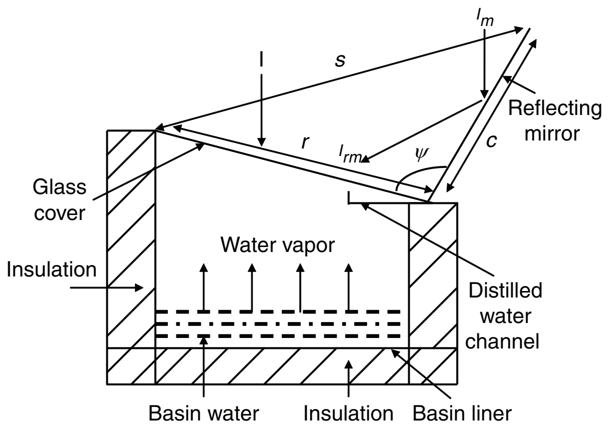

Fig. 1b. A schematic diagram of the single basin solar still with the external mirror.

incident on the still cover a flat plate mirror with an area equals to that of the glass cover (1.015 m^2) is hinged on the short side of the still cover. The mirror is insulated at its back with glass wool (1 cm thick); hence, the mirror can be used as a cover for the still when it is not in use. Fig. 1b shows a schematic diagram of the still with the external reflector. The still is oriented such that the mirror becomes faces south to reflect most of the available solar radiation onto the still cover.

2.1. Mathematical model

When writing the energy balance equations for the still elements (with and/or without the external mirror) the following assumptions have been made:

1. the heat capacities of basin liner, glass cover, reflector and insulating material are negligible compared to that for the basin water;
2. the side losses are negligible;
3. there is no temperature gradient across the thickness of basin water. This assumption is justified by considering a small depth of basin water.

2.1.1. The still without the external mirror

On the basis of the above assumptions, the energy balance equations for the various elements of the still may be written as follows:

Glass cover;

$$IA_g\alpha_g+(h_{rwg}+h_{cwg}+h_{ewg})A_g(T_w-T_g) = h_{rgs}A_g(T_g-T_s)+h_{cga}A_g(T_g-T_a) \quad (1)$$

where I is the total solar radiation incident on the still cover. The radiative h_{rwg}, convective h_{cwg} and evaporative h_{ewg} heat transfer coefficients are calculated using the following correlations due to Dunkle [25]:

$$h_{rwg} = 0.9\sigma(T_w^2+T_g^2)(T_w+T_g) \quad (1a)$$

$$h_{cwg} = 0.884\left[(T_w-T_g)+\left(\frac{p_w-p_g}{2016-p_w}\right)T_w\right]^{\frac{1}{3}} \quad (1b)$$

$$h_{ewg} = 9.15\times10^{-7}\left[\frac{h_{cwg}(p_w-p_g)L_w}{(T_w-T_g)}\right] \quad (1c)$$

where p_w and p_g are the partial pressures of saturated vapor at the basin water and glass cover temperatures, respectively; L_w is the latent heat of vaporization of water.

Basin water;

$$I\tau_g\alpha_wA_w+h_1A_b(T_b-T_w) = (h_{ewg}+h_{cwg}+h_{rwg}) \times A_w(T_w-T_g)+m_wC_w\frac{dT_w}{dt} \quad (2)$$

where h_1 is the convective heat transfer coefficient from the basin liner to the basin water, calculated using the following correlation [26]

$$h_1 = (0.54k_w/b)(Gr\times Pr)^{0.25} \quad (2a)$$

where *Gr* and *Pr* are Grashof and Prandtl dimensionless numbers, respectively. b is the characteristic length taken as the width of the basin liner.

Basin liner;

$$I\tau_g\tau_w\alpha_gA_b = h_1A_b(T_b-T_w)+U_bA_b(T_b-T_a) \quad (3)$$

where $U_b = k_b/x_b$ is the back loss coefficient. k_b and x_b are the thermal conductivity and thickness of the insulating material.

From Eqs. (1) and (3), T_g and T_p are obtained as:

$$T_g = \frac{I\alpha_g+h_2T_w+h_{rgs}T_s+h_{ega}T_a}{h_2+h_3} \quad (4)$$

$$T_b = \frac{I\tau_g\tau_w\alpha_b+h_1T_w+U_bT_a}{h_1+U_b} \quad (5)$$

where $h_2 = h_{rwg}+h_{cwg}+h_{ewg}$ is the total internal heat transfer coefficient from the basin water to the lower surface of the glass cover and $h_3 = h_{rgs}+h_{cga}$ is the total external heat transfer coefficient. Substituting T_g and T_b and using Eqs. (4) and (5), Eq. (2) is solved analytically under the following initial condition

$$T_w(t=0) = T_{wi} \quad (6)$$

where T_{wi} is the initial temperature of basin water. The following formula has been obtained for the basin water temperatures T_w:

$$T_w = \frac{\overline{f(t)}}{a}\left\{1 - \exp\left(\frac{-at}{X}\right)\right\} + T_{wi}\exp\left(\frac{-at}{X}\right) \tag{7}$$

where $\overline{f(t)}$ is the average values of $f(t)$ during a time interval Δt and may be treated as a constant [27]. Mathematical expressions for $f(t)$, a and X which are functions of solar intensity, ambient temperature, various heat transfer coefficients etc, are given in the Appendix.

2.1.2. The still with the external mirror

For the still with the external reflector, the energy balance equations are similar to those for the still without mirror except the solar radiation incident on the still cover I must replaced by the total solar radiation I_t incident on the still cover which include in this case the global solar radiation incident directly on the still cover I and that reflected to the cover from the external mirror I_{rm} (see Fig. 1b).

Mathematically, I_t may be expressed as

$$I_t = I + I_{rm} \tag{8}$$

with

$$I_{rm} = I_m \rho_m F_{mg} A_m / A_g \tag{9}$$

where I_m is the total solar radiation incident on the mirror and ρ_m is the mirror reflectivity. F_{mg} is the view factor between the mirror and the still cover. F_{mg} is expressed as [24]

$$F_{mg} = (c + r - s) / 2r \tag{10}$$

with

$$s = [c^2 + r^2 - 2cr\cos\psi]^{\frac{1}{2}} \tag{11}$$

where ψ is the mirror tilt angle; the angle between the mirror and glass cover. I and I_m are calculated with the aid of a computer program based on Liu and Jordan correlation for calculation of global solar radiation on a tilted surface [24]. Analytical expressions for the T_g, T_b and T_w with the external reflector have the same forms as given by Eqs. (4), (5) and (7) after replacing I by I_t.

2.1.3. Productivity and efficiency of the still

The hourly productivity P_h is calculated using the following equation

$$P_h = h_{ewg}(T_w - T_g) \times 3600 / L_w \tag{12}$$

The daily productivity P_d as well as the daily efficiency without and with mirror are calculated using the following formulas

$$P_d = \sum_{24\,h} P_h \tag{13}$$

$$\eta_d = \frac{P_d L_{w,av}}{(A_p \sum I)\Delta t} \times 100(\%) \tag{14}$$

$$\eta_{dm} = \frac{P_d L_{w,av}}{[A_p \sum (I + I_{rm})]\Delta t} \times 100(\%) \tag{15}$$

where $L_{w,av}$ is the daily average of the latent heat of vaporization of water and Δt is time interval during which the solar radiation is measured.

3. Numerical calculations and experiments

Fig. 2 shows the hourly variations of solar radiation intensity incident on a horizontal surface I_h and ambient temperature T_a on typical summer (17/7/06) and winter (17/1/06) days for Jeddah. These data were employed for numerical calculations where a computer program, based on Liu and Jordan isotropic model [24], was prepared in Pascal language by writing subroutines for calculation of global solar radiation incident on both the mirror I_m and still cover I using the hourly measured values of I_h. Another computer program was developed also in

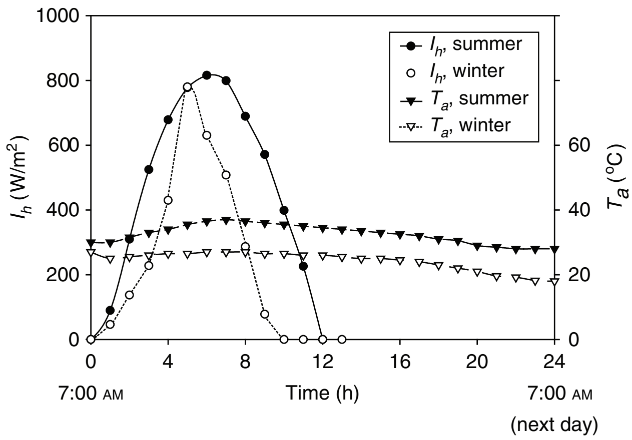

Fig. 2. Hourly variations of solar intensity incident on a horizontal surface (I_h) and ambient temperature (T_a) on typical summer (17/7/06) and winter (17/1/06) days in Jeddah.

Table 1
Relevant parameters used for numerical calculations [24,26]

Relevant parameter	Value	Relevant parameter	Value
A_m(m^2)	1.015	α_g	0.05
τ_g	0.90	k_s (W/m K)	0.059
τ_w	0.95	x_s (m)	0.05
α_p	0.90	C_w (J/kg K)	4190
α_w	0.05	A_b (m^2)	1.0
σ(W/m^2 K^4)	5.669×10^{-8}	ρ_m	0.85
V (m/s) (measured)	Summer, 5.1 Winter, 3.4	k_w (W/m K)	0.628
		ψ (optimum values)	100°, summer 50°, winter

Pascal language for the solution of energy balance equations of the still elements with and without the external mirror. The values of the relevant parameters [24,26] used for numerical calculations are summarized in Table 1.

For the still with and without the external mirror, numerical calculations were started at 7:00 AM assuming the initial temperatures of various components of the still to be equal to ambient temperature. Using known initial values for the various temperatures, different internal and external heat transfer coefficients were calculated. Using these values of heat transfer coefficients along with climatic parameters, the basin linear, basin water and glass cover temperatures were calculated for a time interval Δt (10 min). Numerical calculations indicated that decreasing the time interval beyond 10 min does not significantly improve the accuracy of estimation of the still performance. The hourly productivity P_h is then calculated by using Eq. (12). The procedure was repeated for an additional time interval Δt and so on, until 7:00 am of the next day. The daily productivity as well as the daily efficiency may then be calculated. Numerical calculations have been performed for the still with and without mirror for different masses of basin water in order to study the effect of the external mirror on the still performance during the summer and winter seasons.

In an attempt to validate the proposed mathematical model, the obtained theoretical results were compared with the experimental results that performed on the still in previous work [8,28] under Tanta (Egypt) weather conditions when m_w = 80 kg. The temperatures of different elements of the still and ambient temperature were measured using calibrated NiCr-Ni thermocouples with accuracy 0.5 °C. The horizontal global solar radiation was measured using an Epply EPSP pyranometer coupled to an Epply instantaneous solar radiation meter Model No. 455 with sensitivity of 8.79×10^{-6} (V/W m^2) and accuracy better than 5% in the range from 0 to 2000 W/m^2.

4. Results and discussions

Numerical calculations have been performed for the still with and without mirror on typical summer and winter days. From the results shown in Fig. 2, it is seen that the solar radiation achieve maximum values of 815.45 and 779.87 W/m^2 on the summer (17/7/06) and winter (17/1/06) d, respectively. The corresponding maximum values of T_a are found to be 37 and 27 °C, respectively. Calculated temperature distribution for the still elements without mirror on a summer day (as an example) when the mass of basin water m_w = 50 kg is presented in Fig. 3. The temperatures of the various elements increase with the time of day when the solar radiation increases until they achieve their maximum values at 6:00 PM. The maximum temperatures achieved by the basin liner T_b, basin water T_w and glass cover T_g are obtained as 67.63, 64.72 and 54.56 °C. Fig. 4 depicts variations of hourly productivity P_h of the still without mirror on typical summer and winter days when m_w = 50 kg. It is seen that P_h during the summer is considerably higher than that during the winter as expected due to the higher solar radiation intensity during the summer. From the data shown in Fig. 4, the daily productivity P_d of the still without mirror is calculated to be 4.605 and 2.260 (kg/m^{2}d) with daily efficiencies η_d of 50.69 and 44.76% on the summer and winter days, respectively. Fig. 5a explains variations of hourly productivity of the still with time for different values of m_w in the range 25–200 kg on a summer day when the still is used without mirror. It is clear from the results of Fig. 5a that P_h decreases with increasing m_w during sunshine hours due to the increased time required to heat up the basin water. Overnight, this behavior is reversed due to the increased storage capacity of the basin water itself. At higher values of m_w (m_w > 100), the dependence of P_h on m_w becomes insignificant. The results of Fig. 5a

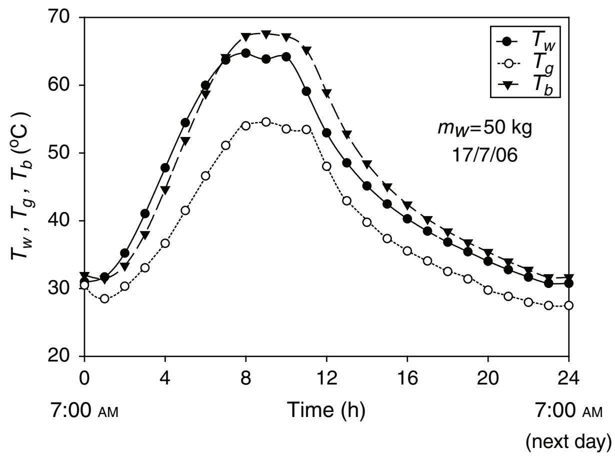

Fig. 3. Temperature distribution for the still elements without mirror on a summer day.

may also be explained in terms of the temperature difference between basin water and glass cover (T_w–T_g); where (T_w–T_g) decreases with increasing m_w during the day which results in a decrease in the evaporative heat transfer coefficient h_{ewg} and vice versa during the night as is shown in Fig. 5b. The dependence of daily productivity P_d and daily efficiency η_d on m_w on typical summer and winter days when the still is used without mirror is summarized in Figs. 6a and b. On the summer day, P_d is found to decrease from 4.180 to 1.514 (kg/m²d) with a corresponding decrease in η_d from 52.37 to 19.07% on increasing m_w from 25 to 300 kg (Fig. 6a). The corresponding decrease in P_d on the winter day is found to be from 2.320 to 1.352 (kg/m²d) with a decrease in η_d from 46.03 to 26.58% (Fig. 6b). At higher values of m_w

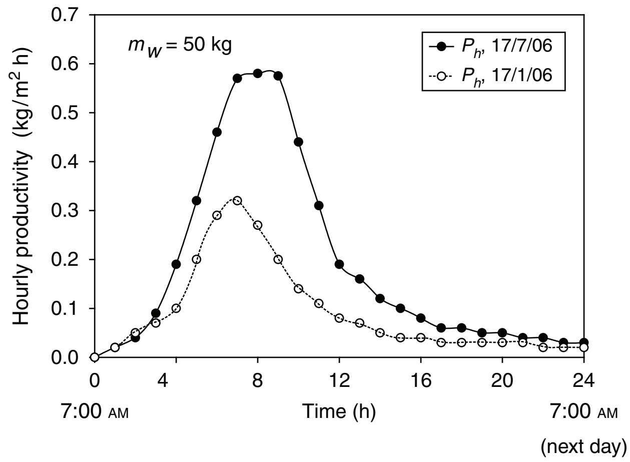

Fig. 4. Variations of hourly productivity (P_h) with time for the still without mirror on typical summer and winter days.

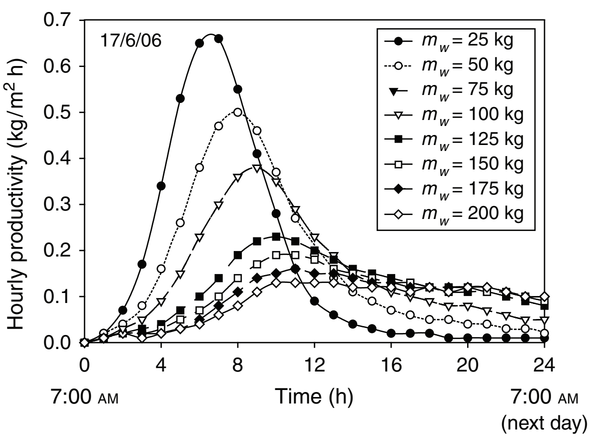

Fig. 5a. Variations of hourly productivity (P_h) with time for different masses of basin water (m_w) when the still is used without mirror on a summer day.

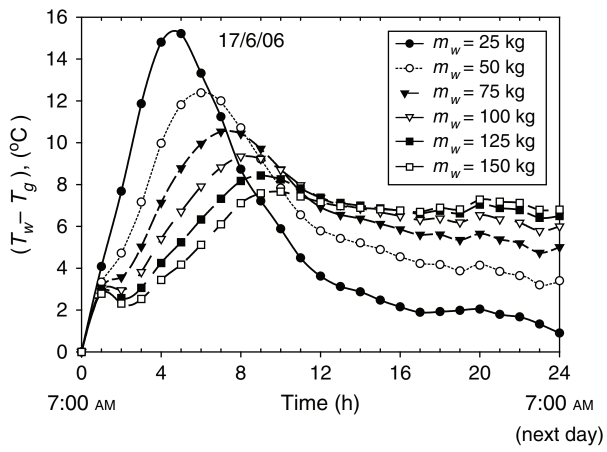

Fig. 5b. Hourly variations of water glass temperature differences (T_w–T_g) with time for different masses of basin water (m_w) when the still is used without mirror on a summer day.

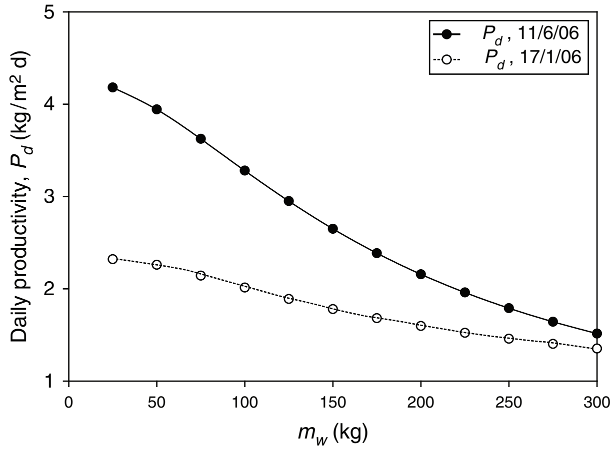

Fig. 6a. Dependence of daily productivity (P_d) on mass of basin water (m_w) on typical summer and winter days when the still is used without mirror.

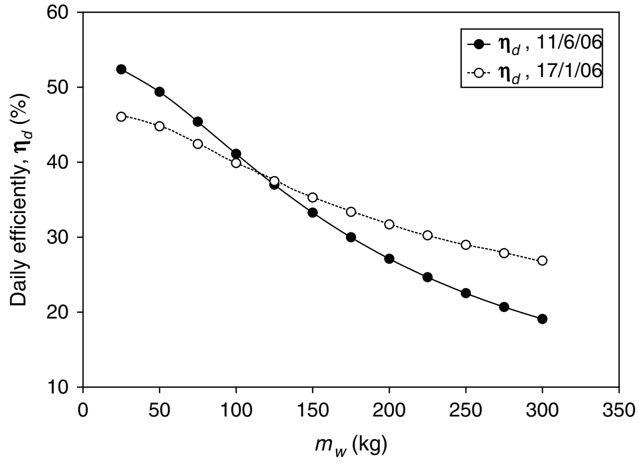

Fig. 6b. Dependence of daily efficiency (η_d) on mass of basin water (m_w) on typical summer and winter days when the still is used without mirror.

greater than 100 kg, both P_d and η_d are decrease slowly with increasing m_w.

In an effort to validate the mathematical model proposed for the still, comparisons between measured and calculated performances have been performed. Figs. 7a and b explain comparisons between measured and calculated temperatures (Fig. 7a) and hourly productivity P_h (Fig. 7b) on a typical summer day (17/9/1997) in Tanta (30° 47′ N), Egypt, when m_w = 80 kg. It is seen that the agreement between measured and calculated temperatures and productivity is fairly good. The maximum values of measured T_b, T_w and T_g (Fig. 7a) are found to be 55.46, 48 and 41 °C. The corresponding theoretical maximum values of different temperatures are 57.02, 49 and 42.1 °C, respectively. The measured daily productivity and efficiency, calculated from the data given in Fig. 7b, are obtained as 2.185 (kg/m²d) and 21.6% compared to 3.150 (kg/m²d) and 26.15% that are obtained theoretically. With the external mirror, the measured daily productivity P_d is found to be 7.300 (kg/m²d) compared to 8.034 (kg/m²d) that calculated using the present model with a relative percentage difference of 9.1% on a typical summer day in Tanta [28]. The differences between measured and calculated results may be due to uncertainties in correlations used for calculations of various heat transfer coefficients and solar radiation incident on the outer mirror and the still cover. Temperature gradient within the basin water and heat capacities of the basin liner, glass cover and insulation materials are not considered in the mathematical analysis and they represent another source of error.

In order to enhance the still productivity, an external reflector with an area equal to that of the still cover is hinged outside the still. Numerical calculations have been carried out with and without the mirror. Some examples of the obtained results are presented in Figs. 8–10. Fig. 8 shows comparisons between the

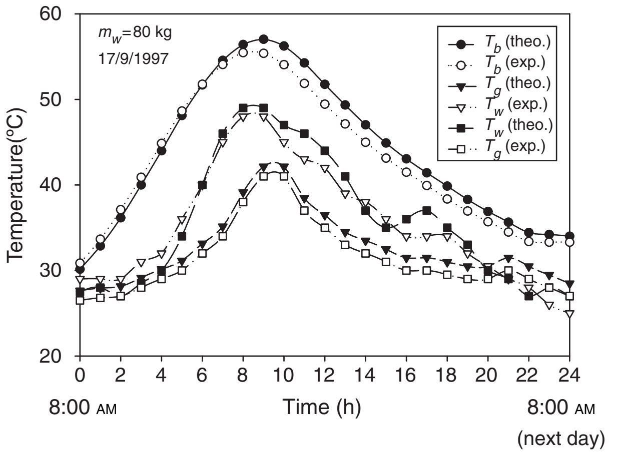

Fig. 7a. Comparisons between measured and calculated temperature responses for the still elements without mirror on 17/9/1997 in Tanta (30° 47′ N), Egypt [8,28].

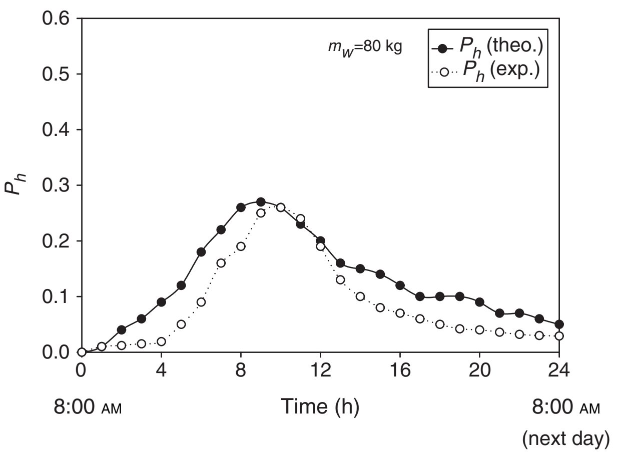

Fig. 7b. Comparisons between measured and calculated hourly productivity (P_h) for the still elements without mirror on 17/9/1997 in Tanta (30° 47′ N), Egypt [8,28].

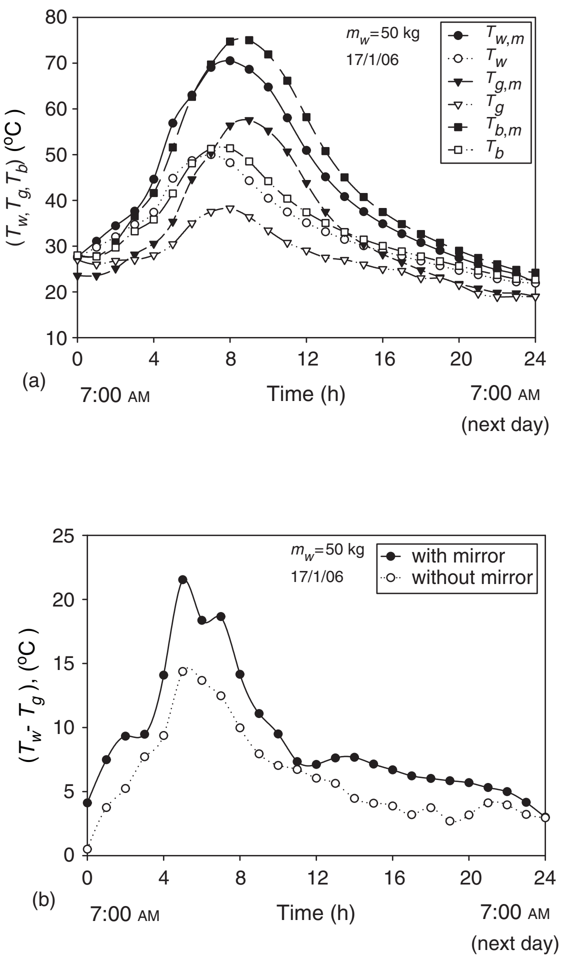

Fig. 8. Hourly variations of the temperatures T_w, T_g and T_b, (a), as well as the water-glass temperature differences ($T_w - T_g$), (b), with and without mirror on a winter day.

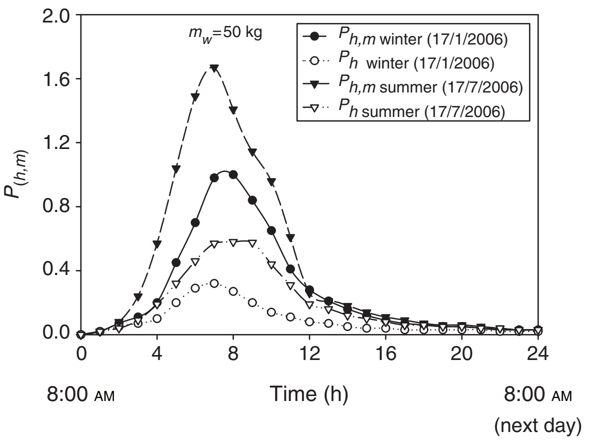

Fig. 9. Comparisons between hourly productivity of the still with ($P_{h,m}$) and without (P_h) mirror on typical summer and winter days.

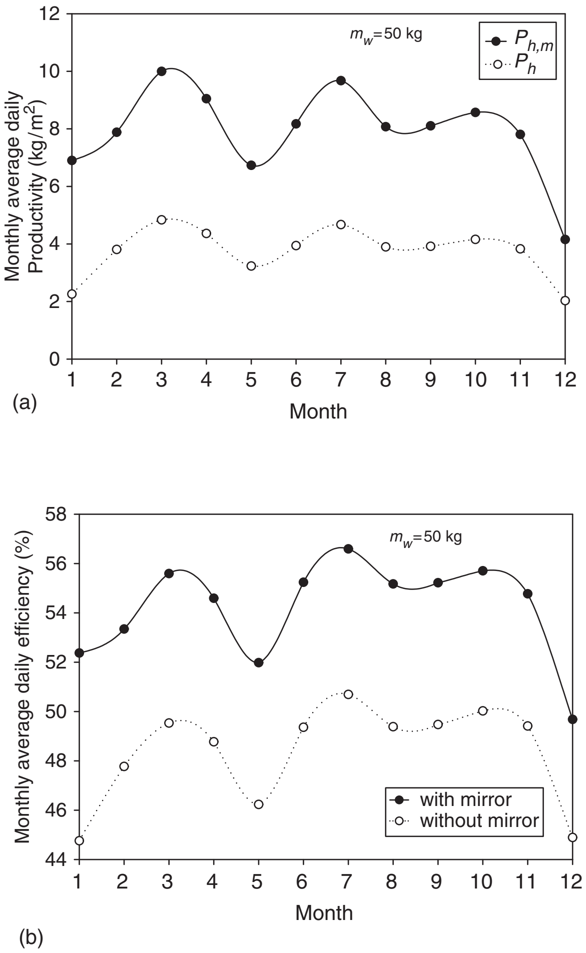

Fig. 10. Monthly average daily productivity (a) and efficiency (b) with and without mirror for the year 2006.

temperatures of the still elements with and without mirror on a winter day. It seen that the temperatures of all elements with mirror are considerably higher than those for the case without mirror; especially during sunshine hours due to the amount of solar radiation reflected from the mirror to the still interior. Moreover, as the solar radiation increases, the basin water temperature increases which results in an increase in the rate of heat transfer from the basin water to the glass cover. This gives rise to an increase in the glass cover temperature. Although T_w and T_g increase when the still is used with the mirror, the water-glass temperature difference (T_w–T_g) also increases (see Fig. 8b) and thereby, the productivity increases. The maximum and daily average values of water-glass temperature differences (T_w–T_g) are obtained as 21.53 and 8.90 °C when the still is used with the mirror compared to 14.37 and 5.99 °C for the still without the mirror. Fig. 9 presents comparisons between variations of hourly productivity with (P_h,m) and without (P_h) mirror on typical summer and winter days. The hourly productivity is seen to increase dramatically during sunshine hours when the still is used with mirror due to the same reasons mentioned above for increasing temperatures when using the mirror. The maximum values of hourly productivity with the mirror are found to be 1.670 and 1.000 (kg/m^{2}h) for the summer and winter days compared to 0.580 and 0.320 (kg/m^{2}h) without the mirror. Therefore, the corresponding daily productivities are obtained as 10.563 and 6.650 (kg/m^{2}d) with mirror compared to 4.605 and 2.260 (kg/m^{2}d) without mirror. It is seen that the daily productivity of the still with mirror is higher than that of the still without the mirror by 56.40 and 66.02% for the summer and winter days, respectively. Therefore, the effect of the mirror on productivity is more pronounced during the winter. These results agree well with those reported by Tanaka and Nakatake. They have indicated that on a winter day, the value of P_d of the still with an inclined external reflector is 16% greater than that obtained when the external reflector is aligned vertically and about 2.3 times higher than that of the still without both the internal and external reflectors [19]. Also, the external reflector can increase the productivity of the wick-type solar still by 9% during the summer season [22].

The horizontal global solar radiation data measured for the year 2006 for Jeddah is employed for estimation of the year-round performance of the still with and without the external mirror. These data have been taken from Meteorology and Environmental Protection Administration, Jeddah. Fig. 10 summarizes the monthly averages daily productivity (Fig. 10a) and efficiency (Fig. 10b) for the still with and without mirror for the year 2006 where the maximum productivity and efficiency are obtained during March and their minimum values are obtained during December. The fluctuations in both the productivity and efficiency curves shown in Fig. 10 are expected due to the expected change in the monthly average of daily total solar radiation incident on the still cover and the outer mirror. The annual daily averages of both productivity and efficiency are obtained as 7.926 (kg/m^2d) and 54.19% with mirror compared to 3.745 (kg/m^2d) and 48.36% without mirror. It is seen from the results of Fig. 10 that the external mirror has improved the daily productivity and efficiency of the still all year round. The annual daily averages of the relative improvement differences of productivity and efficiency are found to be 52.75 and 10.75%, respectively.

5. Conclusions

A transient mathematical model was presented for a single basin solar still with and without an external reflector. The proposed model was validated by comparing the simulated results with the measurements that had been performed for the still under Tanta, lat. 30° 47′ N (Egypt), weather conditions. It was found that the proposed model is able to predict the daily productivity and efficiency of the still with a reasonable value. On typical summer and winter days in Jeddah, the daily productivities were found to be 10.563 and 6.650 (kg/m^2d) with mirror compared to 4.605 and 2.260 (kg/m^2d) when the still is used without mirror. Furthermore, the proposed model was used to predict the annual performance of the still with and without mirror. The annual average of daily productivity with mirror is found to be 52.75% higher than that when the still is used without mirror.

Appendix

Values of the coefficients in Eq. (7)

$$f(t) = \left\{\left(It_g a_w + \frac{It_g a_b t_w h_l}{U_b + h_l} + \frac{I a_g h_3}{h_2 + h_3} \right) + \left(\frac{h_{cga} h_3}{h_2 + h_3} + \frac{U_b h_l}{h_l + U_b} \right) T_a + \frac{h_{rgs} h_2}{h_2 + h_3} T_s \right\}$$

$$a = \frac{U_b h_1}{h_1 + U_b} + \frac{h_2 h_3}{h_2 + h_3}$$

$$X = \frac{m_w c_w}{A_b}$$

Symbols

A	—	area (m^2)
b	—	width of the basin liner (m)
C	—	specific heat (J/kg K)
c	—	height of the mirror (m)
F	—	view factor
Gr	—	Grashof number
h	—	heat transfer coefficient (W/m^2 K)
I	—	solar radiation intensity (W/m^2)
k	—	thermal conductivity (W/m K)
L	—	latent heat (J/kg)
m	—	mass (kg)
P	—	productivity (kg/m^2)
p	—	vapor pressure (N/m^2)
Pr	—	Prandtl number
r	—	width of glass cover (m)
s	—	distance from the upper edge of the mirror to outer edge of glass cover (m)
T	—	temperature (°C)
t	—	time (sec)
U	—	heat loss coefficient (W/m^2 K)
x	—	thickness (m)

Subscripts

a	—	ambient
av	—	average
b	—	basin liner, back
c	—	convection
d	—	daily
e	—	evaporation
g	—	glass
h	—	hourly, horizontal
i	—	initial
m	—	mirror
r	—	radiation, reflected
s	—	insulation, sky
t	—	total
w	—	water

Greek

σ	—	absorptivity
τ	—	transmissivity
ρ	—	reflectivity
σ	—	Stefan-Boltizmann's constant (W/m^2 K^4)
ψ	—	mirror tilt angle (degree)
η	—	efficiency (%)

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