EXPERIMENTAL EVALUATION OF SOLAR STILL MATHEMATICAL MODELS

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ABSTRACT

Experimental evaluation for some of the published mathematical models for water desalination by solar still is presented in this work. The validity and the applicability of these models under the Egyptian weather conditions are examined. Using a computer program, the considered models are evaluated at the same operating conditions. The computer results showed a wide range of discrepancy between the evaluated models. Experimental single-sloped solar still was constructed for the outdoor work within the city of Suez. The obtained results are in a good agreement with some of the considered models.

KEY WORDS:

Solar desalination, Mathematical models, Experimental still, Experimental evaluation.

1. INTRODUCTION

At the situation of water world crisis, saline water desalination technology would become the most important way to face this problem. Egypt is situated in a region of the world where solar radiation intensity is considerably high. At the same time in remote and arid areas of Egypt, the shortage of potable water is a considerable problem. For those regions, the solar desalination is a viable option to provide fresh water from the sea or brackish water. The single sloped solar still, might assist in meeting drinking water requirements of these regions.

The predicted performance of a single effect solar still has been in the technical literature and solar energy textbooks for some times. Mainly, the predictive of the solar still performance is based on empirical relations. The first thermal model for solar still was outlined by Dunkle (1961), and this model based in part on Sharply and Boelter's experiments (1938) on the evaporation of water into quiescent air (Malik *et al.*; 1982). Clark (1990) examined the validity of Dunkle's model. Clark found that the Dunkle's model needs some modifications for the mass transfer relations inside the solar still. Clark's results were obtained from an experimental shallow basin with solar simulator of spotlights bank. Therefore, the applicability of Clark's relations for the outdoor work needs to be investigated. The applicability of Dunkle's original model for a wide range of operating conditions was examined by Adhikari *et al.* (1995). Adhikari found that Dunkle's relations need some modifications for higher range of operating temperatures. In the work of Malik *et al.* (1982), some assumptions were made to simplify the theoretical derivation of the he at transfer coefficient relations. Ghoraba (1987) obtained general relations of heat and mass transfer inside solar still. These relations have the distinction of considering some of the design parameters such as the glass angle and the solar still dimensions. However, Ghoraba uses an immersed electrical heater as an energy source.

Generally, in spite of the many publications on solar stills, there appears to be little in the way of carefully validated mathematical models for predicting long term performance over a wide range of real operating conditions and design characteristics. The objective of this work is to examine the applicability and the validity of these models under the Egyptian weather conditions, theoretically and experimentally.

2. MATHEMATICAL MODELS

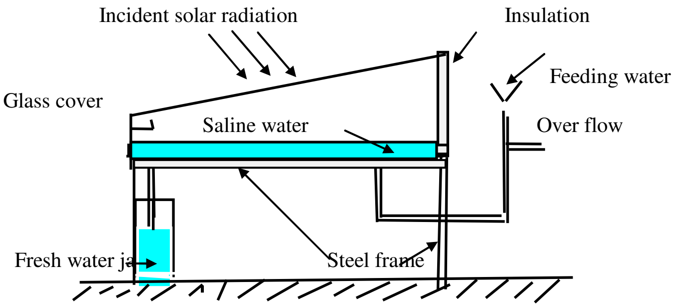

Fig. 1. A schematic diagram of the mounted solar still

The solar still is both a heat and mass transfer device. Most of the incident solar radiation transmitted through the glass cover and absorbed by the basin liner. Water vapor is formed and condensed on the underside of the glass cover to form droplets. Heat of condensation is transferred to the ambient air through the transparent cover, and droplets are collected in a trough as distilled water as shown in Fig. (1). Heat transfer mechanism inside the solar still based on the natural convection mode and radiation from water surface to the glass cover. Convection current occurs as a result of vapor density difference at the evaporating and condensing surfaces (Bloemer *et al.*; 1963).

As different mathematical models have been proposed to describe the simultaneous heat and mass transfer process inside solar stills, so, one of these models is selected as an example to show the applied numerical solution technique. Following the same approach, other models are considered.

In this work, the model of Malik *et al.* (1982) is illustrated with the following assumptions; (i) Thermal temperature gradient across the thickness of glass cover and basin water are insignificant. (ii) Heat transfer coefficient is considered to be constant at the selected interval time. (iii) The heat capacity of the basin liner and the insulation are neglected compared to that of basin water.

The energy balance equations for the glass cover, saline water and basin liner are presented as follow;

$$IA_g\alpha_g + A_w(h_c + h_e + h_r)(T_w - T_g) = h_1 A_g (T_g - T_a) + \rho c x A_g \frac{\partial\theta_1}{\Delta\tau_1} \tag{1}$$

$$I\eta_1 A_w + h_3 A_w (T_b - T_w) = A_w (h_c + h_e + h_r)(T_w - T_g) + (m_w) c_w \frac{\partial\theta_2}{\partial\tau_2} \tag{2}$$

$$I\eta_2 = h_3(T_b - T_w) + U(T_b - T_a) \tag{3}$$

Where, $\eta_1 + \eta_2$ is the optical efficiency (η_o) of the solar still, and defined as the fraction of external incident beam radiation which is absorbed by the water and basin liner. The value of $\eta_1 = 0.27$, and $\eta_2 = 0.58$, as stated by Cooper (1973).

3. NUMERICAL SOLUTION

Since, the climatic conditions such as ambient air temperature (T_a), wind speed (V), and solar intensity (*I*) vary during the day period, the solar still is considered as an unsteady state process. Hence the mathematical model would be represented by a set of nonlinear equations at unsteady state condition as present in Eqs. (1) - (3). This non-linearity because of variation of the heat transfer coefficients inside solar still with temperature. Therefore, it is difficult to obtain an explicit solution for these equations. The model's equations are integrated numerically in time using the finite difference technique, then these equations are linearized by using direct linearization method, Nafey (1988). For the first time interval ($\Delta\tau$), with the initialization of the T_g, T_w and T_b, the computation of individual heat transfer coefficients are performed at a given climatic conditions. With a reasonable specified accuracy, the solution of the model's equations is obtained by iterative method (Gauss-Seidel). Then, T_g, T_w and T_b are updated. The updated temperatures are used in the next time interval as initial values, and so on. For each time interval, the interval solar still productivity is calculated. Then hourly, daily yield and the thermal efficiency are calculated as follows;

Interval yield; $$\dot{m}_{\mathrm{int}} = \frac{h_e(T_w - T_g)}{\lambda} \times \Delta\tau . \tag{4}$$

Hourly yield; $$m_i = \dot{m}_{\mathrm{int}} \times \text{ number of interval per hour} \tag{5}$$

Daily productivity; $$Y = \text{summation of hourly yield} = \sum_{i=1}^{n} m_i \tag{6}$$

Thermal efficiency; $$\eta_{th} = \frac{\sum_{i=1}^{n} m_i * \lambda}{\sum_{i=1}^{n} I_i \times 3600} \tag{7}$$

4. EXPERIMENTAL WORK

In order to examine both the validity and the applicability of the considered mathematical models under the Egyptian weather conditions, an experimental solar still of single sloped glass cover was erected on the site of Faculty of Petroleum and Mining Engineering, Suez Canal University.

The still basin area is 0.25 m^2 and constructed of steel sheet of 2 mm thick. The internal walls were painted with white color to provide a degree of reflection to increase the solar load on the water surface. The external surfaces are insulated with glass wool of thickness 4 cm. The still cover is made of ordinary glass with 3 mm thick making an angle of 15° with respect to the horizontal. U-channel, made of steel sheet, was fixed inside the still for collecting and discharging distilled water outside of the unit. The distilled water is measured directly by a measured jar. Silicon sealant is used to seal the edges of the glass to the frame. In each run, sea water was fed into the basin to a specified depth of 2 cm. Amount of collected distilled water was measured at hourly intervals. The amount of distilled water obtained during night was measured at the next morning. Wind speed was measured by an anemometer. The brine temperature is measured by a digital thermocouple. Solar energy intensity is measured by Silicon Pyrometer with Integrator Solar 118 (model 8347). Figs. (2) and (3) show a typical climatic conditions of solar radiation intensity, ambient temperature and wind speed. These conditions are recorded in Suez city which is situated at 30 latitude in the north east in Egypt at the Suez Gulf.

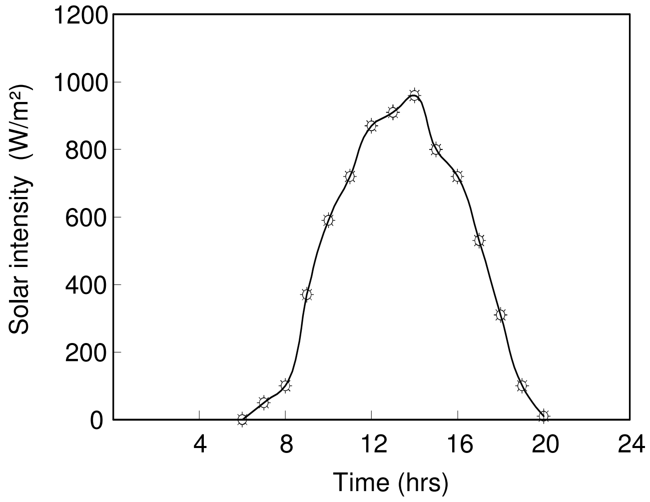

Fig.2. A typical set of data for the solar radiation intensity of 12, 8, 1998

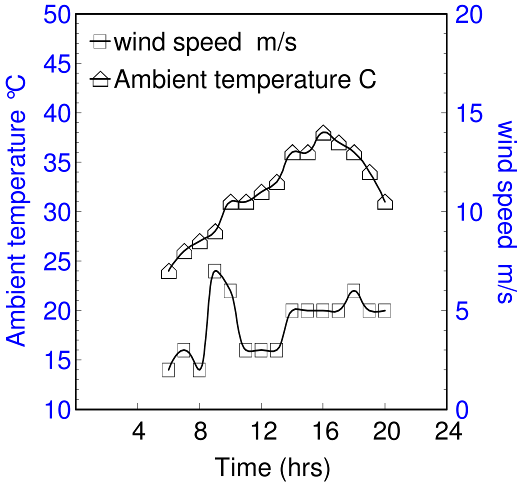

Fig. 3. Wind speed velocity and ambie6t temperature of 12, 8, 1998

5. RESULTS AND DISCUSSION

Under the climatic conditions shown in Figs. (2) and (3), all the considered mathematical models are solved numerically by using the same computer program and the same solution technique. For comparison, the computer results of the solar still productivity, still efficiency and the water temperature for the considered models are present against the experimental work results in Figs. (4), (5), (6) and (7) respectively.

A comparison between the theoretical and experimental results for the hourly and accumulative productivity of the solar still is shown in Figs. (4) and (5). This comparison is performed under the same operating conditions. These figures illustrate that the rate of distilled water from the model of Cooper (1973) is the highest one. The minimal yield was obtained by the model of Malik, (1982) and Clark, (1990). Figure (5) shows that the experimental daily productivity of the solar still is amounting by 5.5 (liter/m^2.day). Also, this value is in a moderate agreement with the results obtained by Clark's model (1990) and Malik's model (1982) .The relations of heat transfer coefficient for both models are present in the Appendix.

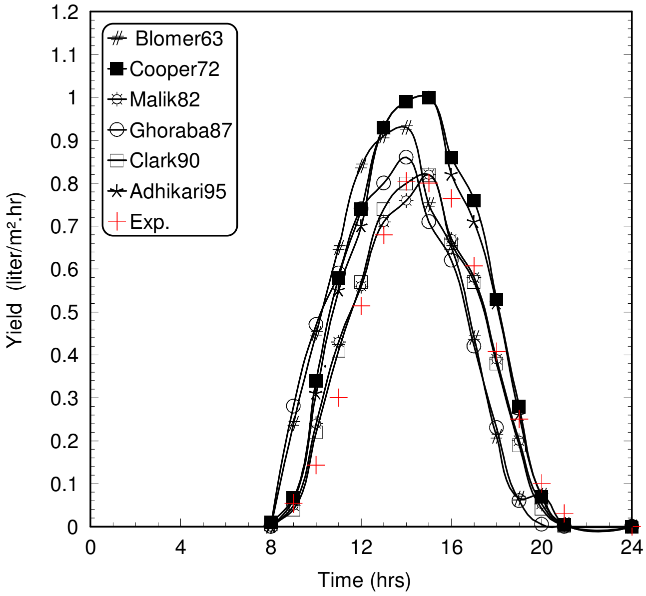

Fig. 4. the hourly output variatian for the solar still models

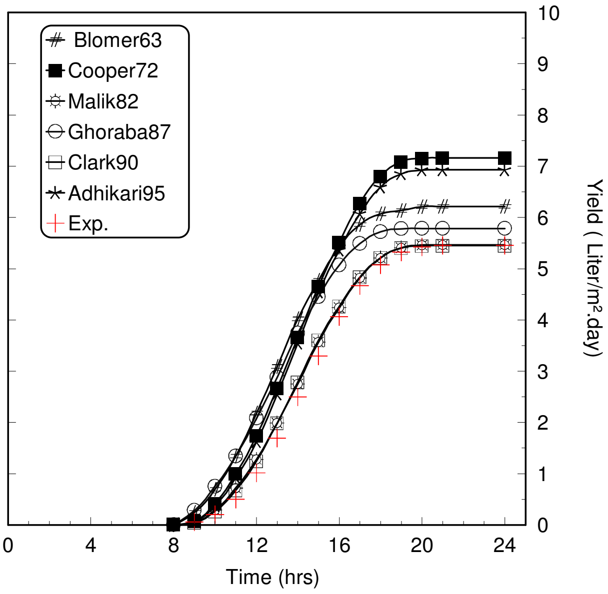

Fig. 5. the daily output variation for the solar still models

Cooper (1973) proved the upper limit of the theoretical efficiency for an ideal solar still as a value of 60 %. At the same operating conditions, the average value of the efficiency for the most of considered models is less than 60 %, which agrees with cooper's finding. The minimum average value of efficiency of 44 % was given by Clark's model (1990) and the maximum value of 60% was given by the model of Cooper (1973) as shown in Fig. (6). The figure shows that, the average theoretical efficiency obtained by Malik's model (1982) is close to the experimental results.

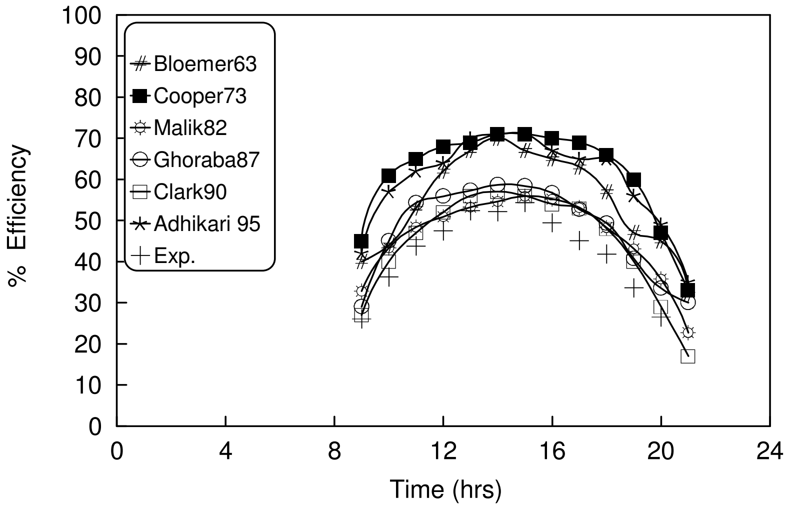

Fig. 6. Solar still efficiency for both the considered models and the experimental results.

Figure (7) indicates a moderate deviation in the basin water temperature for the considered models. The highest value of average basin temperature was 59.6°C and obtained by the model of Cooper (1973). Also, at the same operating conditions the model of Malik *et al.* (1982) gives the lowest temperature with the average value of 54°C. Also, Fig. (7) shows that the average brine temperatures were calculated by Malik's model (1982) are in a moderate agreement with the experimental results.

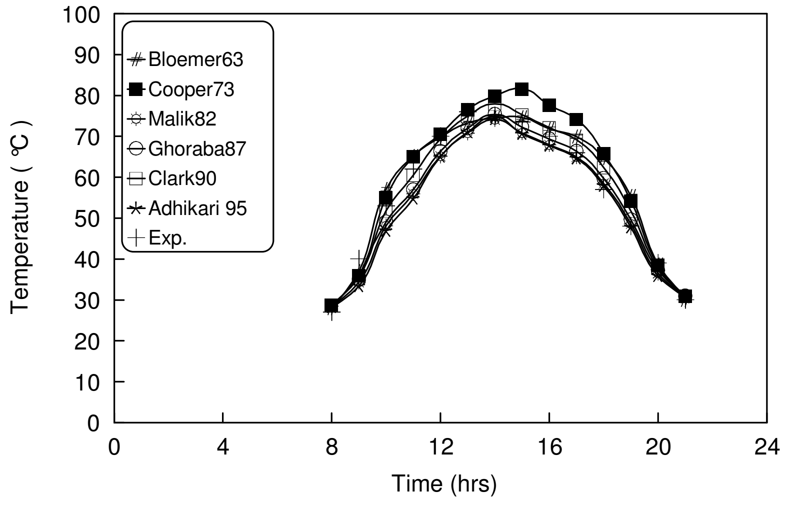

Fig. 7. Basin water temperature variation.

The wide range of deviation between the considered models in the rate of distilled water productivity, solar still efficiency and basin water temperature may be attributed to; (i) Different forms of heat transfer relations used in the considered models; (ii) Different optical solar still efficiency values.

6. CONCLUSION

1. The daily productivity of a single-sloped, solar still is determined experimentally as 5.5 (liter/m^2.day), under the Egyptian climatic of August 1998. Also, the average thermal efficiency of the unit is estimated as 42 %. Under the same operating conditions of 15° glass angle and 2 cm water depth, the basin temperature ranges from 30°C to 76°C.
2. The computer results showed a wide range of discrepancy between the considered models for the estimation of the daily productivity and thermal efficiency of the solar still. Also, this deviation is appeared in the brine temperature variation along the daytime.
3. Both solar still productivity, which are computed by the models of Malik et al. (1982) and Clark (1990), are similar and in a good agreement with the obtained experimental results, under, the Egyptian weather conditions.

NOMENCLATURE

A_g	area of the glass cover, (m^2)
A_w	basin area, (m^2)
C_w	specific heat of water , (J/kg)
h_{ca}	convective heat transfer between glass and ambient , (W/m^2.^{o}C)
h_{ra}	radiative heat transfer coefficient between glass and ambient , (W/m^2.^{o}C)
h_c	convective heat transfer between water and glass cover , (W/m^2.^{o}C)
h_r	radiative heat transfer coefficient between water and glass cover , (W/m^2.^{o}C)
h_3	convection heat transfer coefficient between liner and the wate , (W/m^2.^{o}C)
I_i	solar radiation intensity, (W/m^2)
$\dot{m}_{\mathrm{int}}$	distilled yield of the time interval, (kg/m^2)
$\mathrm{m_i}$	hourly distilled yield, (kg/m^2.*hr*)
$\mathrm{m_w}$	basin water, (kg/s)
n	the day operation hours
$\mathrm{T_a}$	ambient temperature, (^{o}C)
T_g	glass temperature, (^{o}C)
T_w	water temperature, (^{o}C)
T_b	liner temperature, (^{o}C)
$\mathrm{P_w}$	saturation pressure of water at water free suface, (Pa)
$\mathrm{P_g}$	saturation pressure of water at the glass surface , (Pa)
U	overall heat transfer coefficient between the still and the surrounding , (W/m^2.^{o}C)
v	wind speed velocity , (m/s)
ρcx	heat capacity of the glass , (J/^{o}C)
Y	daily yield , (kg/day.m^2)

Greek letters:

λ	latent heat , (J / kg)
η_{th}	Thermal efficiency of the solar still
α_g	glass absorpitivity
θ_1	$T_g^{t+1} - T_g^t$ $({}^0C)$
θ_2	$T_w^{t+1} - T_w^t$ $({}^0C)$
σ	Stefan - Boltzman constant (W / m^2k^4)
$\Delta\tau_1$	time interval of the glass, (sec.)
$\Delta\tau_2$	time interval of the water (sec.)
$\Delta\tau$	selected time interval, (sec)
η_1	fraction of energy absorbed by water of
η_2	fraction energy of the liner

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APPENDIX

1. The model of Malik *et al.* (1982)

$$h_c = 0.8831 * \left((T_w - T_{gi}) + \frac{(p_{sw} - p_{sg}) * T_w}{.2.723 \times 10^4 - p_{sw}} \right)^{\frac{1}{3}}$$

$$h_e = 16.273 \times 10^{-3} * h_c * \frac{(p_{sw} - p_{sg})}{(T_w - T_g)}$$

$$hr = 0.9 * \sigma * (T_w^4 - T_g^4) / (T_w - T_g)$$

2. Clark's model (1990)

$$h_c = 0.8831*\left((T_w - T_{gi}) + \frac{(p_{sw} - p_{sg})*T_w}{.2.723\times10^4 - p_{sw}}\right)^{\frac{1}{3}}$$

$$h_e = \frac{0.5*7\times10^{-9}*h_c(p_{sw} - p_{sg})*\lambda}{T_w - T_g}$$

$$hr = 0.9*\sigma*(T_w^4 - T_g^4)/(T_w - T_g)$$