HEAT AND TRANSFER ANALYSIS IN A CONICAL SOLAR STILL: AN EXPERIMENTAL STUDY

H. E. Gad [a], Sh. Shams El-Din [b], A. A. Hussien [b] and Kh. Ramzy [c]

a Department of Mechanical Power Engineering, Faculty of Engineering Mansoura University, Egypt
b Department of Mechanical Power Engineering, Faculty of Engineering Menoufiya University, Egypt
c Department of Mechanical Engineering, Faculty of Engineering Suez-Canal University, Egypt

ABSTRACT

In this paper, an attempt is made to estimate the heat transfer coefficients of a conical solar still. Many researches and development works tried to enhance the productivity of solar stills using different methods. So in this study the productivity enhancement of solar still by decreasing the shadow effect and maximize utilization of solar radiation is discussed. A new conical solar still was designed and manufactured at faculty of engineering Sheben El-Kom - Egypt (latitude 30.56 N and longitude 31.01 E). The still base area was 0.8 m^2, and the glass (acrylic) cover of still inclined at 31^o which equal to the latitude of Sheben El-Kom. The experimental results of conical solar still were compared with a conventional type solar still which have the same dimensions. The results showed that, the daily productivity for conical and conventional solar stills was 3.38 and 1.93 L/m^2.day respectively. Heat and mass transfer coefficients were evaluated and the Nusselt and Sherwood numbers were calculated with the aid of both evaporation measurements and Chilton-Colburn analogy. The maximum value of the total heat transfer coefficient were 66 and 32 W/m^2.^{o}C for conical and conventional solar stills respectively.The analogy between heat and mass transfer coefficients was also investigated.

Keywords: Solar energy; heat and mass transfer; solar still; conical.

NOMENCLATURE

A	Area of the basin of solar still,	m^2
a and b	Constants	
C	Unknown constant for Nusselt number expression	
C_p	Specific heat of vapor,	J/kg ^{o}C
D	The diffusion coefficient	
d	Characteristic length of solar still,	m
Gr'	Modified Grashof number	
h_{cw}	Convective heat transfer coefficient,	W/m^2K
h_{ew}	Evaporative heat transfer coefficient,	W/m^2K
h_{fg}	Latent heat of vaporization,	J/kg
h_m	The mass transfer coefficient,	W/m^2 ^{o}C
h_{rw}	Radiative heat transfer coefficient from water to cover,	W/m^2 ^{o}C
h_1	Total heat transfer coefficient from water to cover,	W/m^2 ^{o}C
K	Thermal conductivity of the humid air,	W/m K
Le	Lewis number	
M	Molecular weight	kg/mol
m	Number of experimental variables	
Nu	Nusselt number	

n	Unknown constant in the Nusselt expression	
m_{ew}	Hourly distillate yields,	kg/m^2
P	The total pressure	atm
P_g	Partial pressure at cover temperature,	N/m^2
Pr	Prandtl number	
P_w	Partial saturated vapor pressure at water temperature,	N/m^2
Q_{cw}	Convective heat transfer,	W
q_{cw}	Convective heat transfer rate,	W/m^2
q_{ew}	Evaporative heat transfer rate,	W/m^2
q_{rw}	Radiative heat transfer from water to cover,	W/m^2
R	Constant in equation (11)	
R^2	The coefficient of determination	
Ra	Rayleigh number	
R_u	Universal gas constant	
T	The humid air temperature	K
T_a	Ambient air temperature,	^oC
T_b	Basin temperature,	^oC
T_w	Water temperature,	^oC
T_g	Mean glass covers temperature,	^oC
T_s	Mean vapor temperature,	^oC
T_{g1}, T_{g2}	Glass covers temperature,	^oC
T_{s1}, T_{s2}	Vapor temperature,	^oC
$\Delta T'$	Temperature difference between water and inner glass cover,	^oC
t	Time interval	sec

GREEK SYMBOLS

ϵ_{eff}	Effective emissivity, dimensionless
ϵ_g	Emissivity of acrylic cover, dimensionless
ϵ_w	Emissivity of water , dimensionless
σ	Stefan-Boltzmann constant
β	Expansion factor of vapor
μ	Dynamic viscosity of vapor
ρ_v	Density of vapor

1. INTRODUCTION

The need of pure water is important in day-to-day life. The shortage of drinking water is the biggest problem of the world in this century due to population growth and unsustainable consumption rates. The possible water sources are the bore wells, rainwater, and river or lake water. Oceans constitute about 97.5 %, and the remaining 2.5 % fresh water is present in the atmosphere, surface water, polar ice and ground water. This means that only about 0.014 % is directly available to human beings and other organisms [1]. The limitations of solar energy utilization for desalination are the high initial cost for renewable energy devices and intermittent nature of the solar radiation. Brackish or waste water can be converted into potable water using solar stills [2]. El-Sebaii [3] studied theoretically the effect of wind speed on the performance of some different designs of solar stills. The results showed that, the daily productivity increased as the wind speed increased up to a certain velocity. The analysis of a single-basin solar still with a cooling between a double-glass glazing was performed by Abu-Arabi et al. [4]. They observed that, flow of cooling water between the double-glass cover increased the solar still productivity. The effect of using different size sponge cubes inside the still basin was studied by Abu-Hijleh and Rababa'h [5]. The sponge cubes improved the productivity from 18 % to 273 %. Solar desalination unit was studied experimentally and theoretically by Abdel-Rehim and Lasheen [6]. The tested unit contains a parabolic concentrator solar energy with focal pipe and heat exchanger. This modification improved the productivity by an average value of 18 %.

The effect of internal and external reflectors on solar stills performance was studied by Tanaka [7]. The results showed that, the daily productivity of a basin type still can be improved by 70 % to 100 % with using internal and external reflectors. Omara et al. [8] improved the performance of steeped solar still by 125% when internal and external reflectors were used. Also the cost of one liter of the yield for stepped still with reflectors decreased by 0.018$. The effect of cover tilt angle of solar still was studied by Khalifa [9]. The results showed that, the cover tilt angle should be large in winter and small in summer, also the optimum cover tilt angle is close to the latitude angle of the site. Omara et al. [10] studied the effect of different basin shapes on the performance of solar stills. They used finned and corrugated absorbers solar stills. Their results indicate that, using finned and corrugated absorbers improve the productivity of solar stills. In order to increase the productivity of solar stills, Kabeel et al. [11] used different types of nanomaterials with and without vacuum. They used different nanomaterials concentration between 0.02% and 0.2% with a step of 0.02%. The results showed that, the productivity with using cuprous oxide nanoparticles increased by 133.64% and 93.87% with and without using vacuum fan respectively. In the present study a conical solar still is designed and fabricated to obtain maximum yield during the day. This device can be fabricated easily with locally available materials. The maintenance is also cheap and no skilled labor is required. Moreover, it can be a suitable solution to overcome drinking water shortage.

2. EXPERIMENTAL SETUP

In this work, two solar stills were designed and fabricated in order to study as well as to compare the performance of solar desalination systems. The first one is a conical solar still and the second is the conventional solar still. The system consists of a black galvanized iron main tank which is filled with water. A black PVC pipes are connected with the main tank to fill the solar stills with water via the ball valves. A transparent manometer is fixed in used to adjust the water depth in every solar still. Temperature sensors are connected in each solar still to measure the basin, water, space and glass temperatures respectively. The sensors are connected with data acquisition system to record the temperatures every 30 minutes. Fig. (1) shows a photograph of the experimental setup.

Figure (2) shows the schematic diagram of the fabricated experimental conical solar still. The conical solar still consists of a galvanized iron circular base. The overall dimensions of the still are: basin diameter is equal to 100 cm, cone height is equal to 33 cm, basin area is equal to 0.8 m^2.The sides and basin are covered with 0.7 mm thick galvanized iron. The sides and the base are painted black to increase the solar absorptivity. For insulating the system all the sides and base are insulated with foam of 5 cm thick. An inclined circular collection channel is used to collect the condensed water. The condensing surface in the still unit is an acrylic cover (5 mm thickness). The cover of still is adjusted on the edge of the circular side with an angle of 31°, which is the latitude of Sheben El Kom city, Egypt, to maximize the intensity of solar radiation. The conventional solar still (a single basin) has a basin area of 0.8 m^2. High-side wall depth is 70 cm and the low-side wall height is 10 cm, as shown in Fig. (3). The same materials of conical solar still are used to fabricate the conventional solar still. The two models were mounted on a woody frame and thermally insulated of base and all sides.

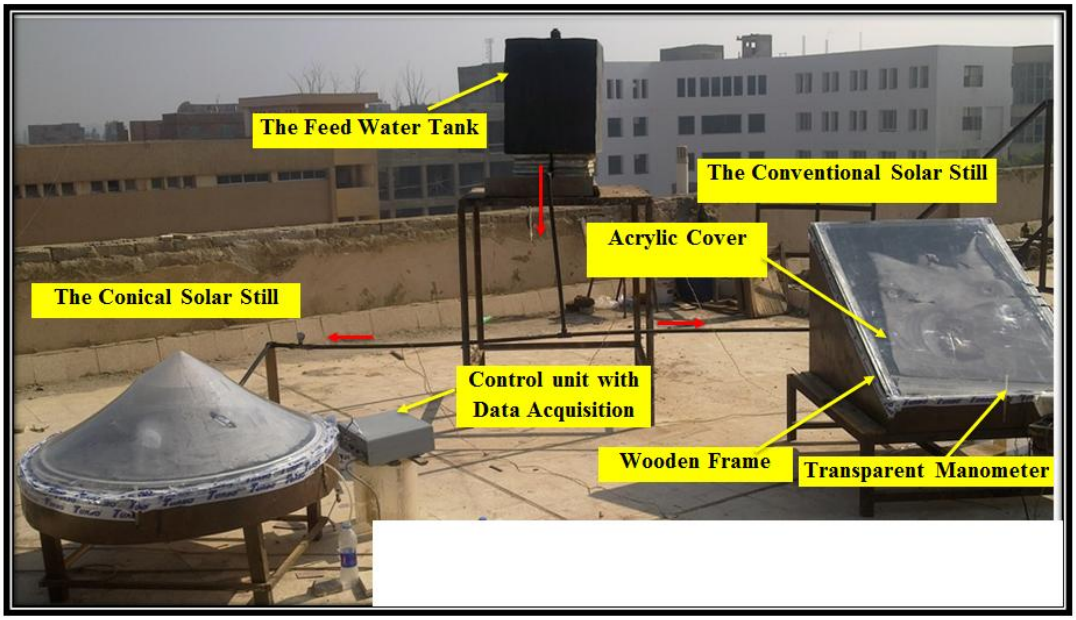

Fig. (1) Photograph of the experimental setup.

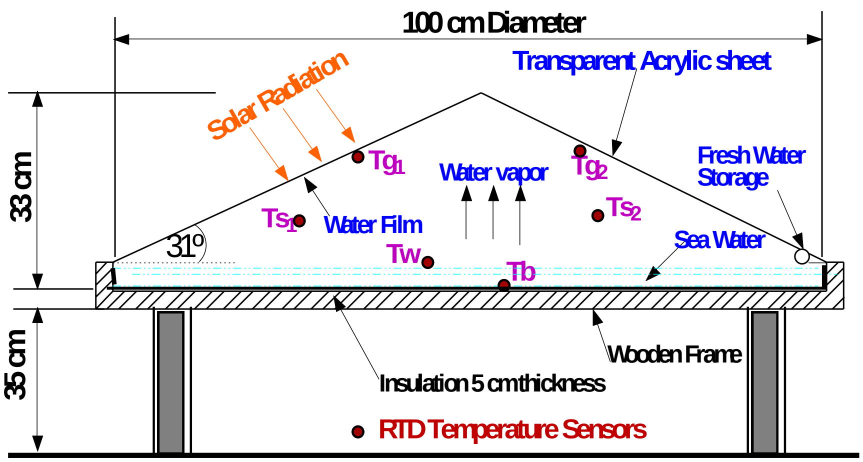

Fig. (2) Schematic diagram of the conical solar still.

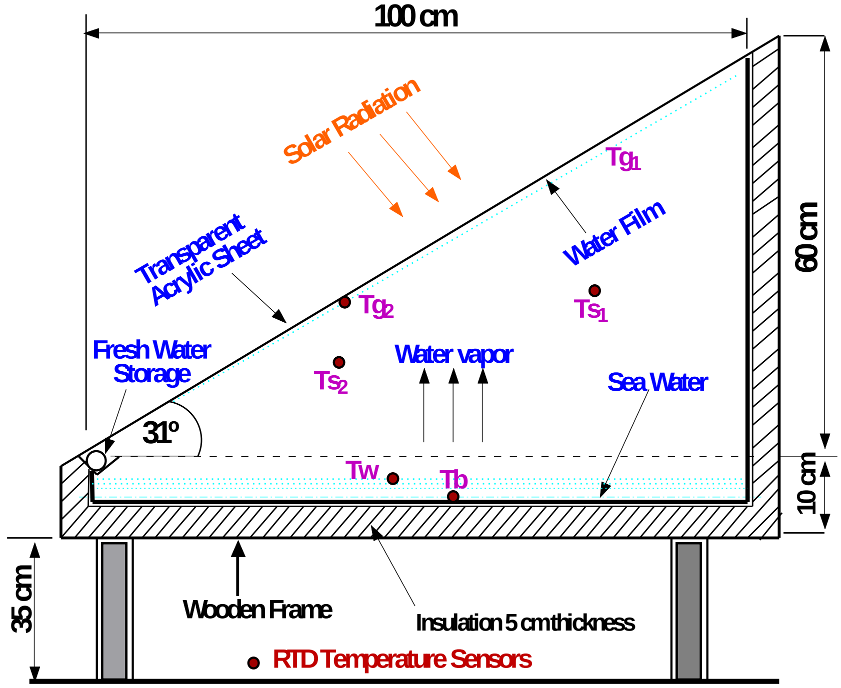

Fig. (3) Schematic diagram of the conventional solar still.

Experiments were conducted at Sheben El-Kom - Egypt and carried out from 7.00 A.M. to 7.00 P.M. during July 2013. Glass temperature, basin temperature, atmospheric temperature, the solar radiation and distilled water productivity were measured every 30 min. The accumulated productivity during this period is also measured. All measurements were performed to evaluate the performance of the conical solar still under the outdoors of Sheben El Kom city conditions. All the experiments are conducted on the best possible clear days for a constant water depth equals to 3 cm in the basin and the measurement of temperatures; distillate output and total solar radiation intensity have been recorded.

Platinum resistance temperature sensors were used to measure the temperatures inside the solar still. The sensors were fixed inside the solar stills at different positions as shown in Figs. (2) and (3). One sensor was used to measure the basin surface temperature (T_b) and another one was used to measure the water temperature (T_w). Two sensors were used to measure the air temperatures inside the solar still (T_{s1}, T_{s2}) and two for the transparent acrylic (T_{g1}, T_{g2}). Eppley pyranometer and calibrated flask were used to measure the global solar radiation and the collected distillate yield respectively during the day. The uncertainty errors for Eppley pyranometer, temperature sensors and the calibrated flask were 0.05 %, 0.56 % and 0.5 % respectively.

2. THERMAL MODEL AND ANALYSIS

The mechanisms of heat transfer through the solar still are basically dependent on the climatic effects and the amount of solar radiation that enters the basin. When the sun’s radiation reaches the Earth it is scattered and absorbed by the atmosphere [12]. Heat transfer in solar still is classified as external and internal heat transfer. External heat transfer is mainly governed by radiation, conduction and convection that are independent of each other. Internal heat transfer is occurred by radiation, convection and evaporation where convection and evaporation are coupled together. Dunkle [13] found an empirical expression for convection heat transfer coefficient and it is a widely used in many literatures. Constant values of C and n in Nusselt relation were calculated depending on the experimental data.

The solar energy heats the water in the still and evaporates it. The generated vapor is freely transmitted from water surface to the top due to buoyancy force caused by density reduction. The circulation of humid air induced by temperature difference between brine and condensation surfaces causing heat and mass transfer by natural convection mode. The internal heat transfer in the still from basin water to condensing cover can take place in three ways mainly by convection, radiation and evaporation [2].

3. 1 Convective heat transfer

The heat transfer inside the still takes place by free convection. This is due to the actions of buoyancy force and the variation in density of humid fluid. To develop the convective heat and mass transfer relationship in solar stills, regression analysis was used. Convective heat transfer is presented by the following equation [14]:

$$Q_{cw} = h_{cw}.A(T_w - T_g) = h_{cw}.A\Delta T \quad (1)$$

where h_{cw} is convective heat transfer coefficient and ΔT is the driving force for heat transfer. The convective heat transfer coefficient, h_{cw}, is a function of fluid properties, still geometry, flow characteristics and operating temperatures. The following expression gives the relation of dimensionless Nusselt number with heat transfer coefficient [15]:

$$Nu = (h_{cw} \times d)/K = C(Gr'.Pr)^n \quad (2)$$

where C and n are constants, Pr and Gr' are the Prandtl and modified Grashof numbers, respectively. Dunkle [13] presented a modified Grashof number for the convective heat transfer by humid air with simultaneous mass transfer of a fluid of lower molecular weight. Gr' and Pr are given by the following expressions. The variables on the right hand side are calculated according to Dwivedi and Tiwari [16].

$$Gr' = \frac{\beta g d^3 \rho_v^2 \Delta T'}{\mu^2} \quad (3)$$

where

$$\Delta T' = \left(T_w - T_g\right) + (P_w - P_g)(T_w + 273.15)/(268.9 \times 10^3 - P_w) \quad \text{and}$$

$$Pr = \frac{\mu C_p}{K} \quad (4)$$

The unknowns C and n in Eqn. (2) are the constant parameters of the convective heat transfer coefficient. These parameters are determined by the linear regression analysis presented by Kumar and Tiwari [15]. Dunkle presented a convective heat transfer correlation as follow:

$$h_{cw} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273.15)}{268.9 \times 10^3 - P_w}\right]^{1/3} \quad (5)$$

3.2 Radiative heat transfer

For a small cover inclination and large width of the still, the water surface and cover are considered as parallel surfaces. The rate of radiative heat transfer from water surface to cover is given by:

$$q_{rw} = h_{rw}(T_w - T_g) \quad (6)$$

The radiative heat transfer coefficient is given by [17]

$$h_{rw} = \varepsilon_{eff}\sigma\left[\left(T_w + 273.15\right)^2 + \left(T_g + 273.15\right)^2\right]\times\left[T_w + T_g + 546.3\right] \tag{7}$$

where

$$\varepsilon_{eff} = \left[1/\varepsilon_g + 1/\varepsilon_w - 1\right]^{-1}$$ and the Stefan-Boltzmann constant is

$$\sigma = 5.669\times10^{-8}\ W/m^2.K^4$$

ε_w and ε_g are the emissivity of the water and acrylic, with values of 0.96 and 0.88 respectively. T_w and T_g are the water and glass temperatures, respectively.

3.3 Evaporative heat transfer

The distilled water amount is evaluated using the relation [18]:

$$m_{ew} = \frac{q_{ew}.A_w.t}{h_{fg}} \tag{8}$$

where

$$q_{ew} = h_{ew}(T_w - T_g) \tag{9}$$

and

$$h_{ew} = 0.01623 h_{cw}(P_w - P_g)/(T_w - T_g) \tag{9a}$$

by substituting Eqn. (2) into Eqn. (9a), h_{ew} is obtained as follows:

$$h_{ew} = 0.01623.\frac{K}{d}.C(Gr'.\Pr)^n.\left[\frac{(P_w - P_g)}{(T_w - T_g)}\right] \tag{9b}$$

on the other hand, substituting Eqns. (9) and (9b) into Eqn. (8):

$$m_{ew} = \frac{0.01623}{h_{fg}}.\frac{K}{d}.A_w.t.(P_w - P_g).C(Gr'.\Pr)^n \tag{10}$$

Eqn. (10) can be rewritten as:

$$\frac{m_{ew}}{R} = C(Gr'.\Pr)^n \tag{11}$$

where

$$R = \frac{0.01623}{h_{fg}}.\frac{K}{d}.A_w.t.(P_w - P_g)$$

$$\ln\left[\frac{m_{ew}}{R}\right] = \ln C + n\ln(Gr'.\Pr) \tag{12}$$

For a linear equation $y = mx + C_o$
where

$$y = \ln\left[\frac{m_{ew}}{R}\right],\quad x = \ln(Gr'.\Pr),\ C_o = \ln C\ and\ m = n$$

Therefore, values of ***C*** and ***n*** can be calculated by linear regression analysis method [15].

4. RESULTS AND DISCUSSION

The weather condition is the important parameter which affects the performance of any solar still. The experimental work was performed on the solar still during one month of the year (June

2013). The maximum value of solar radiation intensity was about 999 W/m^2 for clear sky condition as shown in Figs. (5) and (6).

4.1 Performances of solar stills

Variations of the accumulated distillate during the day time for conical and conventional solar still are shown in figure (4). Experiment was carried out at constant water height equals to 3 cm all over the test. The water height is constant by making up with hot water from the feed water tank. From this figure it can be noticed that, the conical solar still gives the highest productivity compared with the conventional type. The daily productivity for conical and conventional solar stills was 3.38 and 1.93 L/m^2.day respectively.

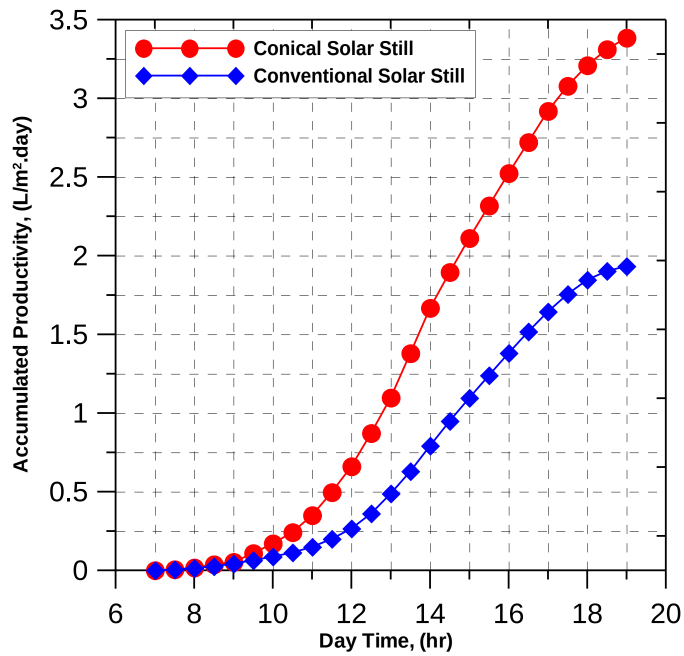

Fig. (4): Comparison between the accumulated fresh water for conical and conventional solar stills with day time.

Figure (5) and (6) represent the variation of ambient, basin, water, space and glass temperatures for conical and conventional solar stills with day time respectively. From Fig. (5), it is observed that, the basin, water, space and glass temperatures reached maximum values of 75.9, 74.3, 70.1 and 66.5 ^{o}C respectively. Also it's clear that, the basin receives and absorbs the energy coming from the sun and the water is heated in still to boiling and steam starts to rise and condensation occurs on the glass and is collected within the waterway to measure the volume in the calibrated flask. The conventional solar still exhibits the same performance of the conical solar still but the basin, water, space and glass temperatures is lower than the conical solar still. The maximum values for basin, water, space and glass temperatures were 57.8, 55.9, 48.9 and 46.5 ^{o}C, respectively as shown in Fig. (6). The ambient air and glass temperature increased and reached its maximum value at about 14 O'clock, and then it began to decrease again. There is a temperature difference between the glass cover and the water along the day time. This helps the vapor to condensate on the inner glass surface and increasing the collected water.

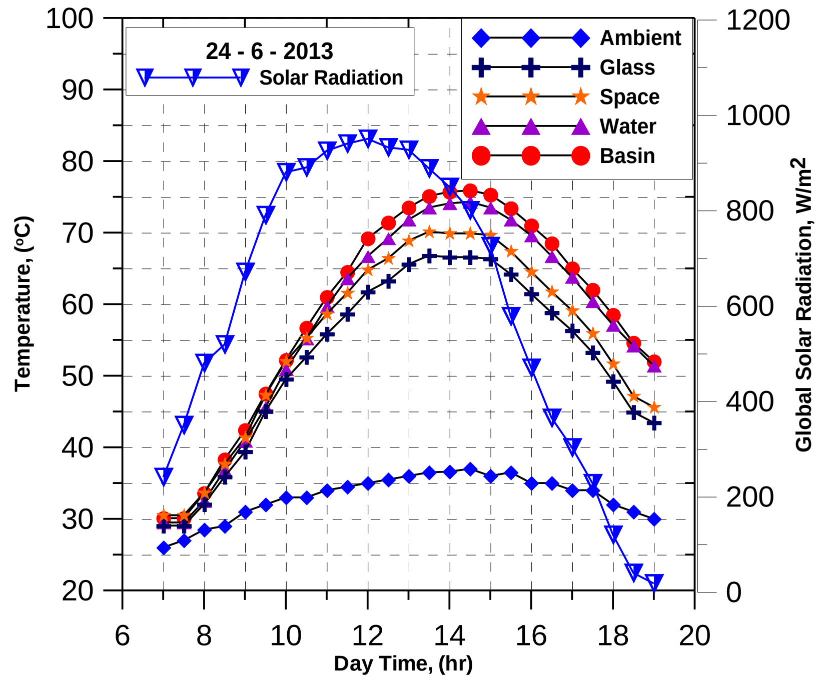

Fig. (5): Variations of ambient, basin, water, glass and space temperatures for conical solar still with day time.

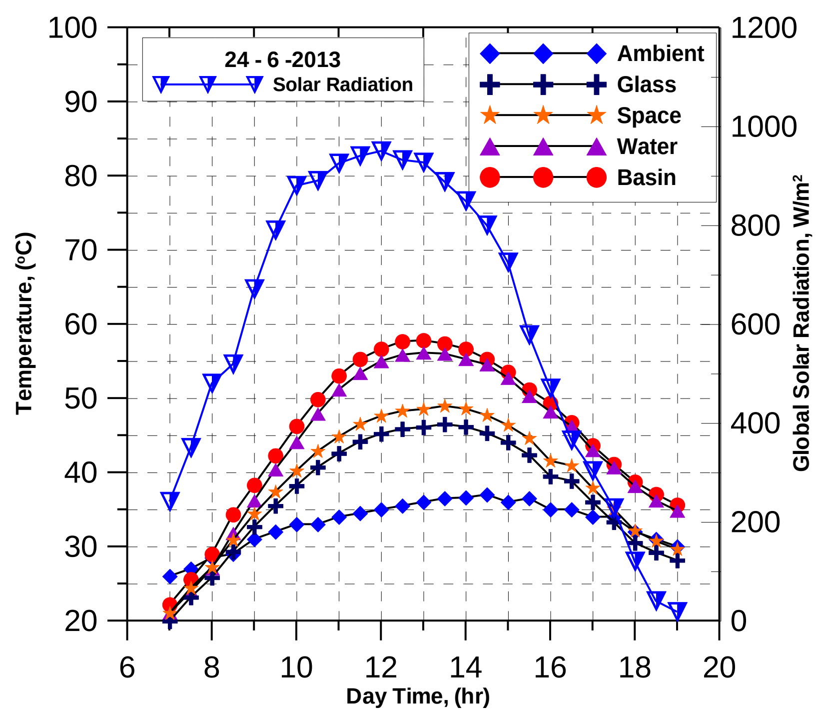

Fig. (6): Variations of ambient, basin, water, glass and space temperatures for conventional solar still with day time.

4.2 Heat and Mass Transfer Coefficients

Convective heat and mass transfer coefficients are important parameters, which are used to measure the resistance of heat and mass transfer between the water surface and the air over that surface. The values of convective, evaporative and radiative heat transfer coefficients for conical and conventional solar stills are given in Table (1). From this table it can be noticed that, the conical solar still gives the highest values of convective, evaporative and radiative heat transfer coefficients during the day time. The maximum evaporative and radiative values depend on the intensity of solar radiation and temperatures of basin and water inside the still. The results reached the maximum value between 13 to 14 O'clock then it begins to decrease to the lower values at day time end.

Table (1): The experimental values of convective, evaporative and radiative heat transfer coefficients for conical and conventional solar stills

Time	Conical solar still			Conventional solar still		
	h_{cw}	h_{ew}	h_{rw}	h_{cw}	h_{ew}	h_{rw}
7.00	0.732	2.689	5.124	0.950	2.225	4.690
7.30	0.732	2.689	5.124	0.852	2.340	4.837
8.00	0.741	3.156	5.278	1.005	3.202	4.98
8.30	0.956	4.951	5.491	1.297	5.081	5.189
9.00	1.148	7.099	5.697	1.484	7.022	5.391
9.30	0.844	6.598	5.984	1.683	9.411	5.578
10.00	1.182	11.447	6.264	1.822	11.812	5.751
10.30	1.501	17.011	6.482	1.986	14.881	5.927
11.00	1.771	23.571	6.714	2.141	18.001	6.072
11.30	1.986	30.282	6.920	2.222	20.330	6.182
12.00	2.044	35.238	7.114	2.286	22.159	6.259
12.30	2.587	44.817	7.116	2.316	23.198	6.303
13.00	2.303	47.264	7.402	2.325	23.549	6.318
13.30	2.399	52.051	7.497	2.283	23.237	6.326
14.00	2.501	54.681	7.509	2.244	22.307	6.294
14.30	2.526	55.450	7.516	2.241	21.549	6.249
15.00	2.447	52.657	7.482	2.172	19.531	6.160
15.30	2.450	49.003	7.357	2.077	17.039	6.041
16.00	2.447	44.512	7.198	2.112	15.521	5.901
16.30	2.357	38.456	7.023	1.981	13.725	5.830
17.00	2.261	33.098	6.855	1.913	11.517	5.662
17.30	2.165	27.776	6.657	1.922	10.303	5.527
18.00	2.174	23.955	6.438	1.921	9.081	5.386
18.30	2.238	21.185	6.227	1.852	8.087	5.300
19.00	2.095	18.035	6.104	1.814	7.464	5.238

The total inner heat transfer coefficient in the solar still is calculated as the sum of the three modes discussed above and is given by:

$$h_1 = h_{cw} + h_{rw} + h_{ew} \tag{13}$$

where h_1 is the total heat transfer coefficient from water to cover, W/m^2 ^{o}C

Figure (7) represents the variations of the total heat transfer coefficient for conical and conventional solar stills with day time. From the analysis of this figure it can be concluded that, the maximum value of the total heat transfer coefficient were 66 and 32 W/m^2.^{o}C for conical and conventional solar stills, respectively. Also from the figure it can be noticed that the maximum value of h_1 appeared at 13.00 o'clock of conventional still and appeared at 14.30 o'clock of conical solar still. The reason of that is the effect of shadow of conventional walls after 12.00 o'clock.

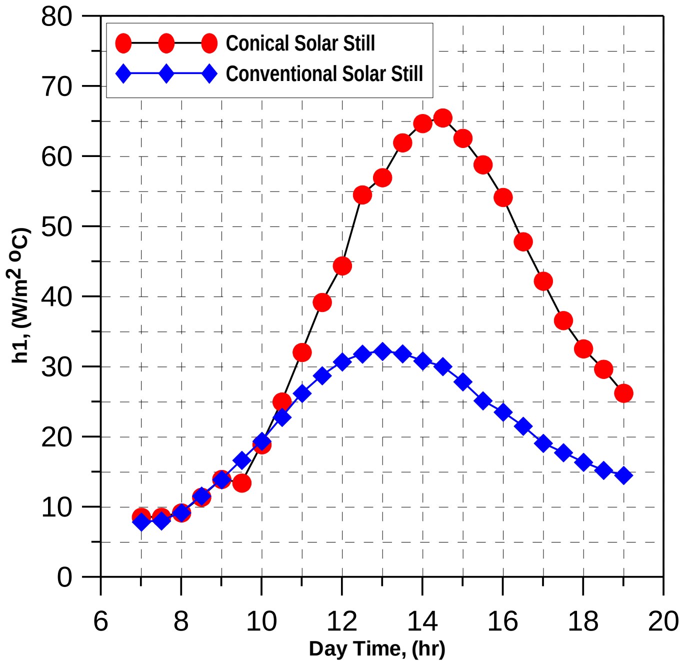

Fig. (7): Variation of total heat transfer coefficient for conical and conventional solar stills with day time.

4.3 Establishment of experimental mass transfer correlation

The evaporation rate in the still is calculated as follows [19]

$$m_{ew} = h_m(\rho_w - \rho_g) \quad (14)$$

ρ_w and ρ_g can be calculated by the perfect gas state equations, Substituting into Eqn. (14), we have

$$m_{ew} = h_m \frac{M}{R_u}\left(\frac{P_w}{T_w} - \frac{P_g}{T_g}\right) \quad (15)$$

where R_u is the universal gas constant.

The convective mass transfer coefficients can be determined using the expression for Sherwood (*Sh*), Grashof (*Gr*) and Schmidt (*Sc*) numbers as follows:

$$Sh = \frac{h_m d}{D} \quad (16)$$

and

$$Sc = \mu_v / (\rho_v . D) \quad (17)$$

where *D* is the diffusion coefficient and given by [20]:

$$D = 1.87x10^{-10} \cdot \frac{T^{2.072}}{P} \quad (18)$$

where *P* is the total pressure in atm and *T* is the humid air temperature in K.

The experimental values of Sherwood (*Sh*) number were validated according to Chiltone Colburn analogy, the relation between heat and mass transfer coefficients for air-water vapor mixture can be expressed with a good accuracy as [20]:

$$h_{cw} = \rho_v . C_p . Le^{2/3} . h_m \quad (19)$$

where *Le* is the Lewis number, $Le = K / D$

Table (2) shows the experimental values of Nusselt and Sherwood numbers for conical and conventional solar stills. From this Table it can be noticed that, the *Nu* of conical solar still gives the highest values and the maximum value is 94.1. Also the values of Sherwood number of conical solar still are higher than the conventional solar still.

Table (2): The experimental values of Nusselt and Sherwood numbers for conical and conventional solar stills

Time	Conical solar still		Conventional solar still	
	Nu	***Sh***	*Nu*	***Sh***
7.00	30.494	29.227	9.733	9.351
7.30	30.494	29.227	8.648	8.302
8.00	30.616	29.321	10.123	9.710
8.30	39.060	37.367	12.904	12.36
9.00	46.378	44.323	14.600	13.974
9.30	33.618	32.086	16.394	15.676
10.00	46.453	44.282	17.588	16.804
10.30	58.388	55.607	19.006	18.145
11.00	68.179	64.871	20.350	19.415
11.30	75.790	72.054	21.006	20.031
12.00	77.364	73.496	21.535	20.529
12.30	97.933	93.036	21.776	20.755
13.00	86.174	81.778	21.843	20.817
13.30	89.430	84.839	21.440	20.433
14.00	93.184	88.397	21.100	20.111
14.30	94.100	89.264	21.123	20.137
15.00	91.268	86.587	20.555	19.603
15.30	91.827	87.157	19.766	18.861
16.00	92.302	87.659	20.236	19.322
16.30	89.585	85.135	19.056	18.200
17.00	86.553	82.307	18.553	17.734
17.30	83.572	79.535	18.771	17.955
18.00	84.751	80.730	18.907	18.097
18.30	88.121	84.016	18.316	17.539
19.00	82.938	79.117	18.001	17.243

4.4 Analogy between heat and mass transfer coefficient

Based on the analogy between heat and mass transfer, a correlation in the form of Eqn. (20) may be suggested as follows:

$$\left(\frac{Nu}{Gr.Pr}\right)=a.\left(\frac{Sh}{Gr.Sc}\right)^{b} \quad (20)$$

where *a* and *b* are constants, which may be obtained with the aid of the experimental data of dimensionless parameters for different solar stills by linear regression analysis.

Some authors used the Chilton–Colburn analogy to determine the mass transfer coefficient in terms of the heat transfer coefficient. In this work, however, the analogy between heat and mass transfer is achieved by drawing the relation between (*Nu/Gr.Pr*) as a function of (*Sh/Gr.Sc*), as shown in figure (8). From this figure it can be concluded that, there is a linear relationship between heat and mass transfer coefficients for the tested solar stills.

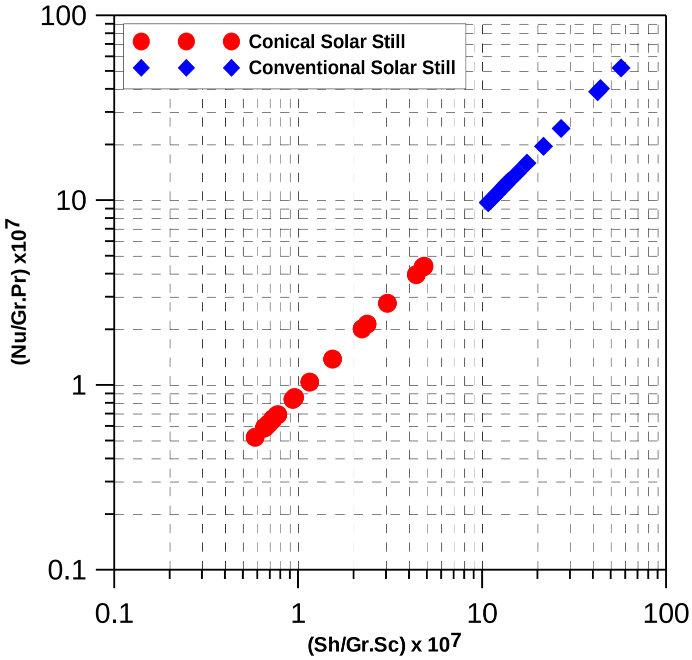

Fig. (8): Variation of parameter (Nu/Gr. Pr) and (Sh/Gr. Sc) for conical and conventional solar stills.

5. COMPARISONS OF CALCULATED RESULTS AND EXPERIMENTAL MEASUREMENTS

Figures (9), (10) and (11) represent a comparison of the theoretical and experimental measurements of accumulated productivity, the Nusselt and Sherwood numbers respectively. From these figures, it is clear that, the present model provides a good agreement between the theoretical results and the experimental values of accumulated productivity, (*Nu*) and (*Sh*) and the theoretical data bounded around the straight line.

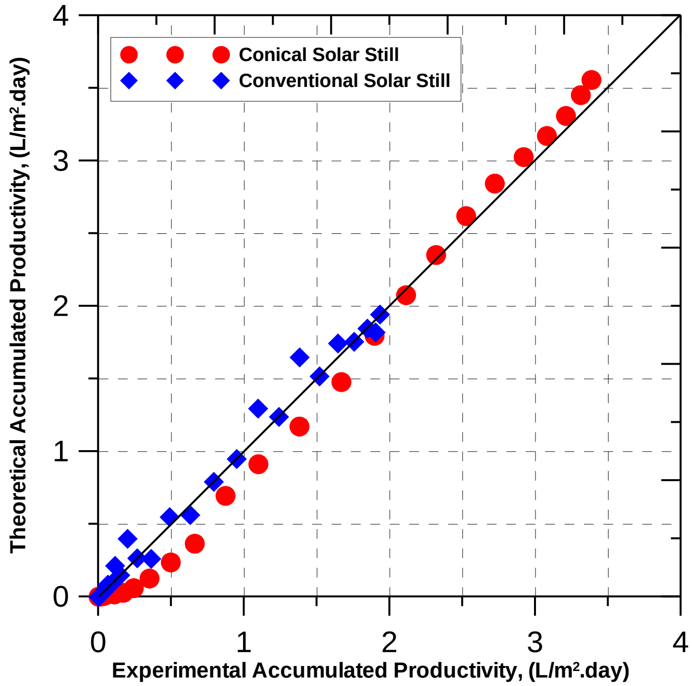

Fig. (9): Comparison of the experimental and theoretical accumulated productivity for conical and conventional solar stills.

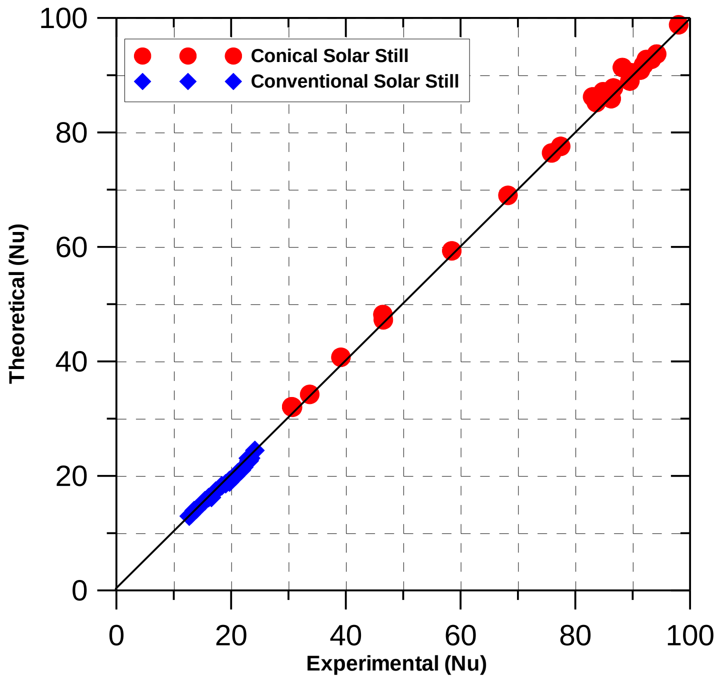

Fig. (10): Comparison of the experimental and theoretical Nusselt number (Nu) for conical and conventional solar stills.

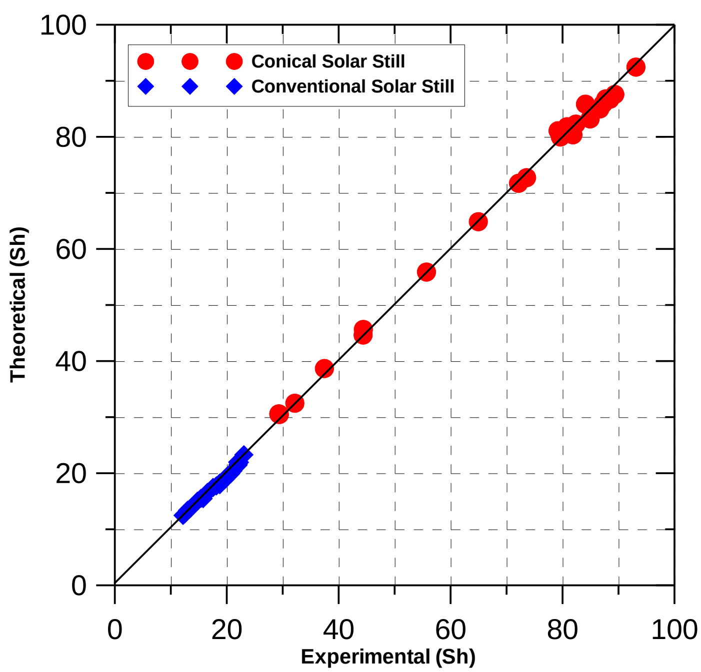

Fig. (11): Comparison of the experimental and theoretical Sherwood number (Sh) for conical and conventional solar stills.

Figure (12) shows the experimental values of Sherwood number and the calculated Sherwood number according to Eqns. (16) and (19) for conical and conventional solar stills. From the analysis of this figure, it can be noticed that, the present model results gives agreement with the predicted values of Chilton–Colburn analogy relation. Table (3) represents the percentage of deviation between the experimental and predicted values of accumulated productivity, the Nusselt and Sherwood numbers of conical and conventional solar stills. From this table it's clear that, the maximum deviation between the experimental and predicted values is 4.976 %. This indicates that the correlation proposed by this paper can predict well the still's performance.

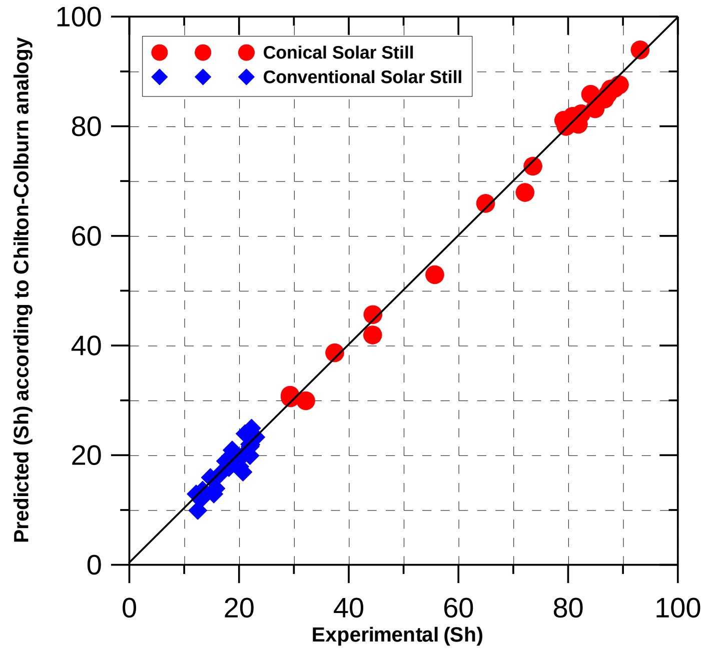

Fig. (12): Comparison of the experimental and calculated Sherwood number according to Chilton–Colburn analogy relation for conical and conventional solar stills.

Table (3): The percentage deviation between experimental and predicted values for the tested solar stills

Solar Still	**Accumulated Productivity, (L/m^2.day)**	**The Nusselt Numbers**	**The Sherwood Numbers**
	% Dev.	**% Dev.**	**% Dev.**
Conventional solar still	4.93	3.03	3.01
Conical solar still	5.06	2.20	2.50

6. EXPERIMENTAL CORRELATIONS FOR HEAT AND MASS TRANSFER COEFFICIENTS

In order to evaluate the conical solar still performance accurately, precise expressions have to be used for calculating the heat and mass transfer coefficients in the solar stills. The proposed empirical correlations for describing the analogy between heat and mass transfer for solar still are given in Table (4). This table also presents the values of the coefficient of determination (R^2) as well as the values of constants. The importance of these empirical correlations is attributed to the possibility of determination the mass transfer coefficients with the aid of the heat transfer coefficients with a sufficient accuracy. The proposed empirical correlations could be used for the prediction of the average mass transfer coefficients for the conical solar still with a good accuracy.

Table (4): The proposed empirical correlations for describing heat, mass and the analogy between heat and mass transfer for the conical solar still

No.	Empirical Correlations	*C*	*n*	R^2
1	$Nu = C.(Gr'.Pr)^n$	16.527	0.343	0.999
2	$Sh = C.(Gr'.Sc)^n$	16.548	0.339	0.999
3	$Nu/(Gr.Pr) = C.\left(Sh/(Gr.Sc)\right)^n$	0.904	1.002	0.998

7. CONCLUSIONS

In this work, a new model of solar stills was designed, fabricated and experimentally tested during daytime under outdoors of Sheben El-Kom city, Egypt climatic conditions. The heat and mass transfer coefficients predicted by the proposed equations were in good agreement with the experimentally obtained values. The analogy between the heat and mass transfer showed a linear relationship between the dimensionless parameters (*Nu/Gr.Pr*) and (*Sh/Gr.Sc*). General empirical correlations for describing the analogy between the heat and mass transfer for conical solar still were also introduced

REFERENCES

Bendfeld, J., Broker, Ch., Menne, K., Ortjohann, E., Temme, L., Vob, J., and Carvallo, P.C.M., 1998, "Design of a PV-powered reverse osmosis plant for desalination of brackish water," Proceedings of 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria, pp. 3075-3077.

Sampathkumar, K., Arjunan, T.V., Pitchandi, P. and Senthilkumar, P., 2010, "Active solar distillation-A detailed review", Renewable and Sustainable Energy Reviews, Vol. 14, pp. 1503–1526

Twidell, J., and Weir, T., 1986, Renewable Energy Resources. 2nd edition. The University Press, Cambridge.

El-Sebaii, A. A., 2000, "Effect of wind speed on some designs of solar stills", Energy Conversion and Management, Vol. 41, pp. 523-538.

Abu-Arabi, M., Zurigat, Y., Al-Hinaib, H. and Al-Hiddabib, S., 2002, "Modeling and performance analysis of a solar desalination unit with double-glass cover cooling", Desalination, Vol. 143, pp. 173-182.

Abu-Hijleh, B. and Rababa'h, H. M., 2003, "Experimental study of a solar still with sponge cubes in basin", Energy Conversion and Management, Vol. 44, pp. 1411–1418.

Abdel-Rehim, Z. S. and Lasheen, A., 2007," Experimental and theoretical study of a solar desalination", Desalination, Vol. 217, pp. 52–64.

Tanaka, H., 2009, "Experimental study of a basin type solar still with internal and external reflectors in winter", Desalination, Vol. 249, pp. 130–134.

Omara, Z. M., Kabeel, A. E. and Younes, M. M., 2014, "Enhancing the stepped solar still performance using internal and external reflectors", Energy Conversion and Management, Vol. 78, pp. 876-881.

Khalifa, A. N., 2011, "On the effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes", Energy Conversion and Management, Vol. 52, pp. 431–436.

Omara, Z. M., Hamed, M. H. and Kabeel, A. E., 2011, "Performance of finned and corrugated absorbers solar stills under Egyptian conditions", Desalination, Vol. 277, pp. 281–287.

Kabeel, A. E., Omara, Z. M. and Essa, F.A., 2014, "Improving the performance of solar still by using nanofluids and providing vacuum", Energy Conversion and Management, Vol. 86, pp. 268-274.

Dunkle, R.V., 1961, "Solar water distillation, the roof type solar still and a multi effect diffusion still, International developments in heat transfer", ASME Proceedings of International Heat Transfer, Vol. 5, pp. 895–902

Velmurugan, V. and Srithar, K., 2007, "Solar stills integrated with a mini solar pond-analytical simulation and experimental validation", Desalination, Vol. 216, pp. 232-41.

Kumar, S. and Tiwari, G.N., 1996, "Estimation of convective mass transfer in solar distillation system", Solar Energy, Vol. 57, pp. 459–64.

Dwivedi VK. and Tiwari GN., 2009, "Comparison of internal heat transfer coefficients in passive solar stills by different thermal models: an experimental validation", Desalination, Vol. 246 (1-3), pp. 304-18.

Sharma, V.B. and Mallick, S.C., 1991, " Estimation of heat transfer coefficients, upward heat flow and evaporation in a solar still, Trans. ASME, Solar Energy, Vol. 113, pp. 36.

Tiwari G.N., Dimri V., Singh U., Chel A. and Sarkar B., 2007, "Comparative thermal performance evaluation of an active solar distillation system", International Journal of Energy Research, Vol. 31, pp. 1465–82.

Hongfei, Z., Xiaoyan, Z., Jing, Z. and Yuyuan, W., 2002, "A group of improved heat and mass transfer correlations in solar stills", Energy Conversion and Management, Vol. 43, pp. 2469–2478

Cengel, Y. A., 2006, "Heat and mass transfer: a practical approach. 3rd edition. New York: Mc Graw Hill.