



Improvement of Solar Still Productivity by Energy Absorbing Plates

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ABSTRACT

A solar still is a viable option when the demand of potable water does not exceed more than 3 litres. Enhancement in distillate output from the solar still is a main goal of many researchers all over the world. In this research, the effect of copper and aluminum plates on distillate output is investigated experimentally as well as theoretically at different water depths under the same climate conditions. In solar stills, first we used solar still augmented with copper plates, second with aluminum and third without any plate called passive solar still. An energy balance equation was applied to solar still for calculation of theoretical distillate output of a solar still with different plates. Three experiments still of 1 m² in area were constructed from locally available materials. In this work, it was found that the experimental and theoretical results are in good agreement. It was also found that using copper plate in a solar still increases distillate output by 20% (at water depth of 3 cm) and 32% (at water depth of 6 cm) compared with passive solar still, and using an aluminum plate increases distillate output by 10% (at water depth of 3 cm) and 20% (at water depth of 6 cm).

Keywords: Solar still, Copper plate, Aluminum plate, Distillate output

1. Introduction

Solar desalination is a process of separation of pure water from saline or sea water using solar energy. The use of solar still is a cheap method of providing clean water. The solar assisted desalination system can be classified as passive and active solar still. The simple and conventional solar still consists of a black painted mild steel basin to receive solar radiation in which saline or sea water is kept. The basin is placed in a trapezoidal wooden box which is covered by a glass cover at an angle of latitude to the horizontal to retain the solar thermal energy inside the still due to the greenhouse effect. Thus, the solar thermal energy is utilized to heat the saline or sea water. The space between the basin and wooden box is packed with glass wool

insulation to reduce heat loss through the sides and bottom of still. Due to existence of phase equilibrium between the saline water surface and air space, the air just over the water surface will be saturated with water vapour corresponding to the water temperature. With the solar radiation incident on the saline water, its surface temperature increases which causes an increase in the saturated pressure of water vapour near the water surface corresponding to water temperature. At this time, the partial pressure of water vapour near the glass surface will be less than that above the water surface since the temperature of the inner surface of the glass cover is lower. The temperature difference between the water and inner glass cover surface causes the difference in partial pressures of water vapour which causes the transfer of water vapour from the basin water

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surface to glass surface, and the condensation on the inner surface of the glass. [1].

The existing conventional solar stills suffer lots of drawbacks, which make them inefficient for domestic as well as industrial use. Many researchers have tried to improve the productivity as well as efficiency of solar stills. To mention a few, Kudish et al. [2] proposed a new low cost solar still. Cooper [3] explained the effect of reducing depth of water inside the solar still on distillate output. Voropoulos et al. [4] and Lawrence [5] coupled a flat plate collector with single basin solar still to improve the distillate output. Riffat [6] made an innovative design of a multi effect solar still. Sharma and Mullick [7] estimated various heat and mass transfer coefficients of solar stills. Ishibashi [8] studied the enhancement in boiling heat transfer of water and salt mixture in restricted space of compact tube bundle. Hongfei et al. [9] suggested a group of improved heat and mass transfer correlations in basin type solar stills by experimenting on multi-stage stacked tray solar stills with comparison to single slope single basin solar stills. Kumar and Tiwari [10] have developed a thermal model for solar distillation units based on linear regression analysis to determine convective mass transfer coefficient for different Grashofs number. Panchal et al. [11, 12] used different plates in the solar still to improve the efficiency of solar still. They found 15% and 20% improvement in efficiency of solar still by use of M. S. Plate and G. I. Sheet.

This research paper represents the copper plate and aluminium plate for maintaining film evaporation in solar still. The effect of using the plates investigated experimentally as well as theoretically at different water depths under the same climate conditions of Mehsana, Gujarat.

2. Mathematical Modelling

Using the measured values like solar insolation, wind velocity, ambient temperature at the Mehsana as input data, the daily distillate output of a solar still is calculated. The mathematical model is developed according to the energy balance equations. It follows following assumptions.

- Temperature gradient across the thickness of glass cover is insignificant;
- Heat capacity of basin liner and insulation are neglected;
- Plate is opaque with constant absorptivity of 0.90; and

- Heat transfer coefficient is considered to be constant at the selected time interval.

1. Energy balance for the glass cover:

$$0.5 IA_g + \alpha_g + \frac{K_g}{x}(T_{gi} - T_{go}) = (h_{ca} + h_{ra})A_g(T_{go} - T_a) \quad (1)$$

$$0.5 I\alpha_g + h_{condu}(T_v - T_{gi}) + (h_c + h_r)(T_{w1} - T_{gi}) = \frac{K_g}{x}(T_{gi} - T_{go}) + mc_p \frac{\partial \theta}{\partial T} \quad (2)$$

2. Energy balance for moist air:

$$h_c(T_{w1} - T_v) = h_{condu}(T_v - T_{gi}) + U_1 A_s (T_v - T_i). \quad (3)$$

3. Energy balance for water liner above the black plate:

$$I\eta_1 + h_{cpw}(T_{p1} - T_{w1}) = h_c(T_{w1} - T_v) + (h_c + h_r)((T_{w1} - T_{gi}) \quad (4)$$

4. Energy balance for water liner above the plate:

$$0.5 I\eta_2 = h_{cpwu}(T_{p1} - T_{w1}) + \frac{K_p}{t_p}(T_{p1} - T_{p2}). \quad (5)$$

$$0.5 I\eta_2 + \frac{K_p}{t_p}(T_{p1} - T_{p2}) = h_{cpw1}(T_{p2} - T_{w2}). \quad (6)$$

5. Energy balance for water liner above the plate:

$$h_{cpw1}(T_{p2} - T_i) = K_w \frac{\partial t}{\partial y} + U_2 A_s \frac{\Delta y}{2}(T_i - T_a) \quad (7)$$

6. Energy balance for nth Layer of water:

$$\rho C_p \Delta y \frac{\partial T}{\partial \tau} = K_w \frac{\partial^2 T}{\partial y^2} \Delta y - U_2 A_s \Delta y (T_i - T_a) \quad (8)$$

7. Energy balance for bottom layer of the water block:

$$-K_w \frac{\partial T}{\partial y} = h_{cwp}(T_i - T_n) * U_2 A_s \frac{\Delta y}{2}(T_i - T_a) \quad (9)$$

8. Energy balance for basin liner:

$$U_2 A_s \frac{\Delta y}{2}(T_i - T_a) = h_{cwp}(T_i - T_n) \quad (10)$$

Here, climate conditions like ambient temperature (T_a), wind speed (V) and solar insolation (I) vary from day to day. Hence, they are assumed as unsteady state processes. So, the mathematical model is represented by several nonlinear unsteady state conditions because they are varying with time. Hence, such nonlinearity causes variations in heat transfer coefficient inside the solar still and explicit solution is very difficult to obtain. Due to all of the above reasons, it is necessary to apply numerical techniques to predict the performance of a solar still by use of temperature variables. Distillate output of solar still is calculated by following equation:

$$m_{solar\ still} = \frac{h_{cond}(T_v - T_{gi})}{L}$$

The hourly distillate output is determined by following equation:

$$m_{solar\ still} = \sum m_{solar\ still}$$

3. Experimental set up

Three single slope single basin solar stills designed and fabricated from locally available materials of City Mehsana, Gujarat. Each unit consists of a mild steel box with four sides 3 mm thick. Two sides were rectangular, while other sides had trapezoidal shape. Two holes were made in each solar still, one for filling the water and another for distillate output. The base of solar still was painted black to increase the solar radiation absorptivity. Here, black chrome paint having 0.90 absorptivity was used in each solar still. Outer side of the base and sides of solar still insulated by the help of 5 cm thick FRP (fiber reinforced plastic) having thermal conductivity of 0.03 W/mK. A distillate collection trough was used for each solar still to collect condensed distillate output. This trough was fixed to the lower rectangular side of the solar still box. Instead of ordinary glass, each solar still unit consisted of toughened glass with an inclination angle of 15 degrees. Figure 1 shows the experimental set up.

The first and second solar stills consisted of saline water with copper and aluminium plates, respectively, and the third one was a passive solar still. Experiments were performed by using different depths of water, namely 3, 4 and 6 cm.



Fig.1. Experimental set up

4. Results and discussion

Experimental data involving solar insolation and distillate output collected during daytime were recorded on a daily basis every hour from 9 am to 5 pm during sunshine hours only.

4.1. Variation of Time versus insolation

Figure 2 shows the daily insolation of solar intensity with respect to time. It shows that insolation increases from 9 am to 2 pm due to bright sun radiation, and then from 2 to 5 pm, insolation decreases. Hence, it is obvious that the higher the insolation incident on solar still water, higher evaporation and condensation, which leads to higher distillate output from solar still.

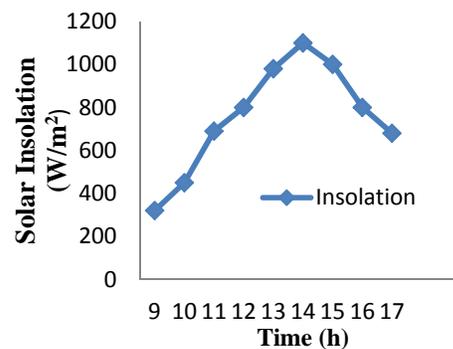


Fig. 2. Relation between Time and Solar Insolation

4.2. Variation of distillate output of solar still by varying depth of saline water

Figures 3, 4, and 5 show the effect of varying the depth of saline water on solar still. Copper is a material which possesses good thermal conductivity compared with aluminium and mild steel. Hence, here higher distillate output was of gained by solar stills with copper plate. Here, when the plate is put in the solar still, two distinct zones were formed. The one above the plate called higher temperature

zone, and that below the plate is called lower temperate zone. From, the heat transfer rate in higher temperature zone was more and hence evaporation and condensation lead to the higher distillate output of a solar still. Lower zone of the plate maintained heat inside the basin; hence, whenever heat is required to transfer, it will supply the heat to the upper basin. Hence, 6 cm depth of saline water increases distillate output compared with 4 and 3 cm depth.

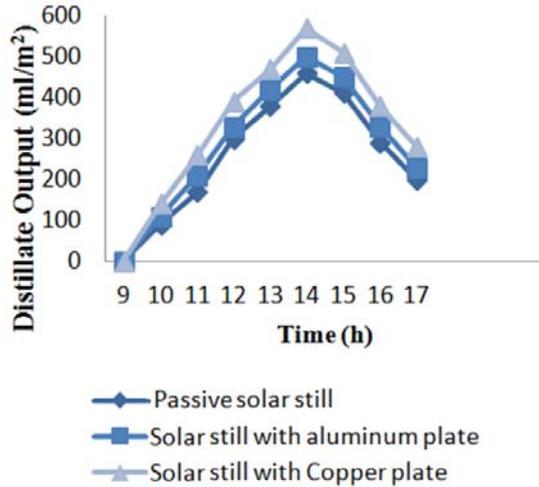


Fig. 3. Relation between Time and Distillate output of solar still having 3 cm thickness (1st March, 2012)

4.3. Accumulation of distillate output of solar still by varying the depth of saline water

Figures 6,7 and 8 show comparisons between the accumulative distillate outputs of a solar still having different depths inside the solar still. In all figures, it is clear that distillate output is linearly increasing from morning to evening. Least output is achieved at 9 am and highest at 5 pm. Table 1 shows a comparison of various depths of the solar still with energy absorbing plates.

4.4. Variation of distillate output of solar still by varying depth of saline water

A comparison between experimental and theoretical results of the distillate output of the solar still at different water depths and energy absorbing plates are shown in Figures 9, 10, and 11. The figures show that as the water depth increases, distillate output increases.

This has happened because using plates inside the solar still decreases the temperature of bottom layer of water, and hence the thermal

energy stored at any depth of water is decreasing. Therefore, it can be said that the distillate output increase by increase of depth of water.

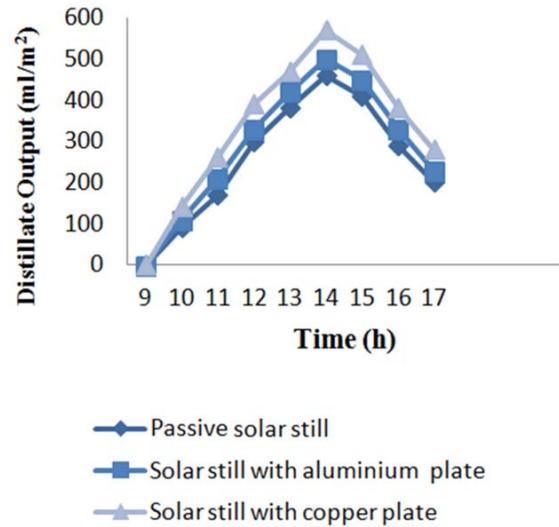


Fig. 4. Relation between Time and Distillate output of solar still having 4 cm thickness (2nd March, 2012)

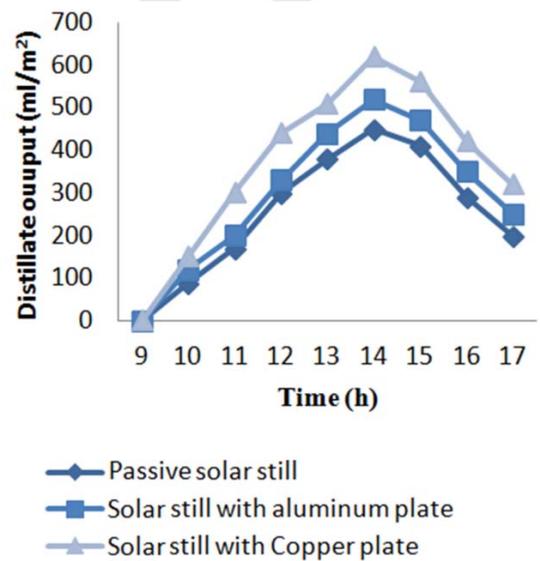


Fig. 5. Relation between Time and Distillate output of solar still having 6 cm thickness (3rd March, 2012)

The obtained experimental and theoretical results comparison shows that, at a water depth of 3 cm, there is an increase in distillate output by 10% and 20% at 4 cm to 32% at 6 cm of depth of saline water.

The highest percentage of the distillate output is achieved because in the higher depth of saline water, there is an advantage of maintaining thermal energy in the water below the energy absorbing plate in a small quantity. Figures 9,10 and 11 shows good agreement of experimental results with theoretical results.

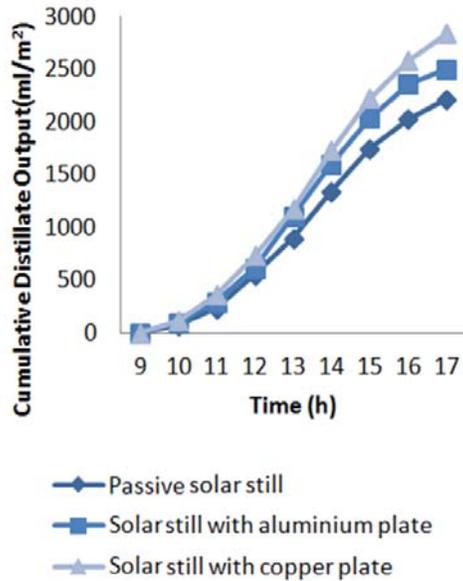


Fig. 6. Accumulative distillate output of solar still having 3 cm thickness (1st March, 2012)

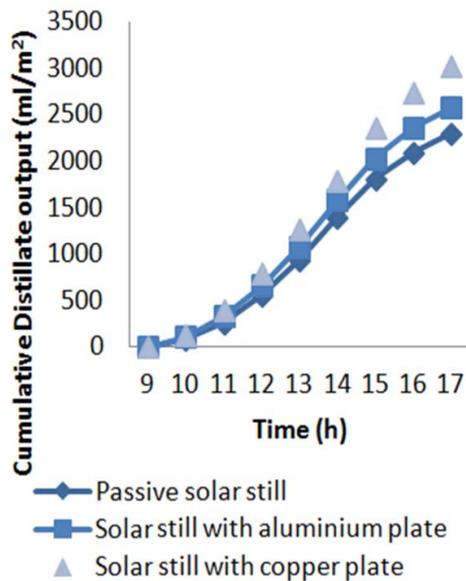


Fig. 7. Accumulative distillate output of solar still having 4 cm thickness (2nd March, 2012)

Table 1. Comparison of experimental cumulative output of solar still with depth of water and energy absorbing plates

| Sr. No. | Depth in cm | A.* output of passive solar still (mL/m ²) | A.* output of solar still with aluminium plate (mL/m ²) | A.* output of solar still with copper plate (mL/m ²) |
|---------|-------------|--|---|--|
| 1 | 3 | 2240 | 2500 | 2840 |
| 2 | 4 | 2300 | 2580 | 3030 |
| 3 | 6 | 2290 | 2680 | 3320 |

A.* = Accumulative

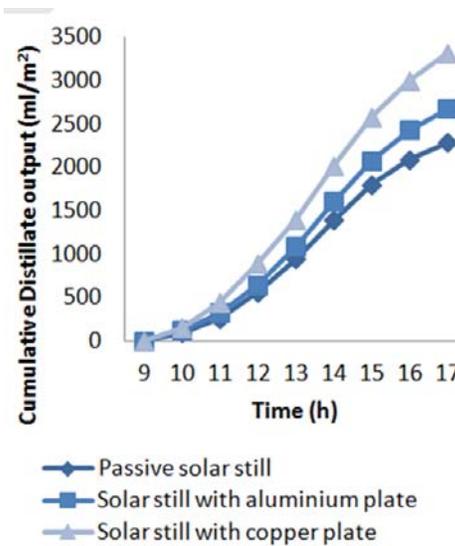


Fig. 8. Accumulative distillate output of solar still having 6 cm thickness (3rd March, 2012)

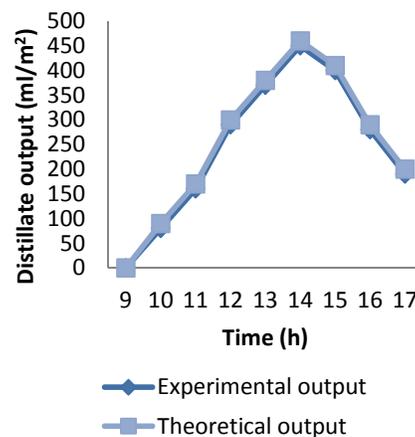


Fig. 9. Comparison of experimental distillate output and theoretical distillate output of solar still having 3 cm thickness (1st March, 2012)

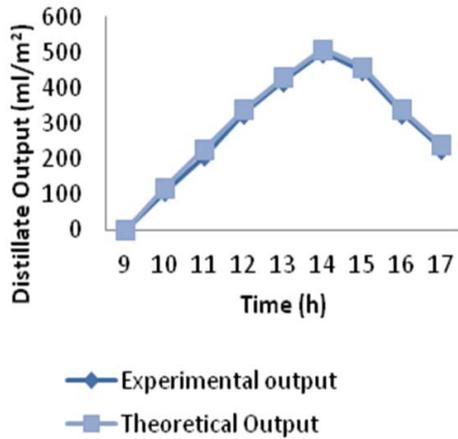


Fig. 10. Comparison of experimental distillate output and theoretical distillate output of solar still having 4 cm thickness (2nd March, 2012)

To show experimentally and theoretically, the percentage increase of solar still by use of different energy absorbing plates, following equation is used.

Percentage increase =

$$\frac{\text{Theoretical output} - \text{Experimental Output}}{\text{Theoretical output}} * 100$$

Table 2 shows the theoretical distillate output of a solar still having different energy absorbing plates. In theoretical accumulative distillate output is always more due to absence of manual effort as well as losses encountered in a solar still.

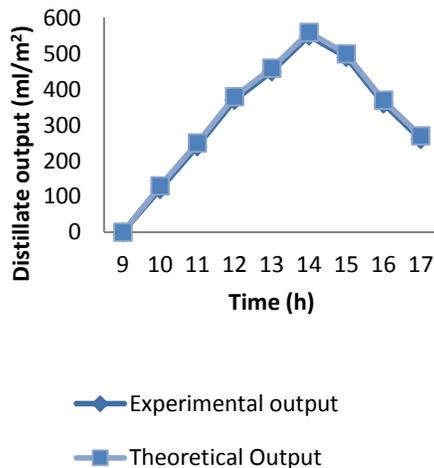


Fig.11. Comparison of experimental distillate output and theoretical distillate output of solar still having 6 cm thickness (3rd March, 2012)

5. Conclusion

The following points are concluded:

- Results obtained by experiment and mathematical modelling are in good agreement with different energy absorbing plates and depth of saline water.
- Copper is a better energy absorbing plate compared to aluminium due to its higher thermal conductivity.
- Higher depth of water inside the basin leads to the higher distillate output due to maintaining a constant thermal energy in the basin.
- Cumulative theoretical and experimental distillate output is more for solar still having copper plate compared with aluminium plate and passive solar still.
- Using Copper plate, there is an increase of 32% distillate output at depth of 6 cm compared with passive solar still.

Table 2. Comparison of theoretical cumulative output of solar still with depth of water and energy absorbing plates

| Sr. No. | Depth in cm | cumulative output of passive solar still (mL/m ²) | cumulative output of solar still with aluminum plate (mL/m ²) | cumulative output of solar still with copper plate (mL/m ²) |
|---------|-------------|---|---|---|
| 1 | 3 | 2300 | 2600 | 2950 |
| 2 | 4 | 2400 | 2670 | 3190 |
| 3 | 6 | 2380 | 2810 | 3490 |

6. Nomenclature

- I Solar Insolation (Watt/ m²)
- h Time, hour
- V Wind Velocity (m/s)
- h_{cond} Conduction heat transfer coefficient (W/ m²°C)
- h_e Evaporative heat transfer coefficient (W/ m²°C)
- h_{ca} Convective heat transfer coefficient between glass and ambient (W/ m²°C)
- h_{ra} Radiative heat transfer coefficient between glass and ambient (W/ m²°C)
- h_c Convective heat transfer coefficient between glass cover and water (W/ m²°C)
- h_r Radiative heat transfer coefficient between water and glass cover (W/ m²°C)
- h_{cpwu} Heat transfer coefficient between plate and upper water liner (W/ m²°C)
- h_{cpwl} Heat transfer coefficient between plate and lower water liner (W/ m²°C)
- U₁ Overall heat transfer coefficient between

| | |
|------------|---|
| | side wall and surrounding ($W/m^2\text{ }^\circ\text{C}$) |
| U_2 | Overall heat transfer coefficient between bottom wall and surrounding ($W/m^2\text{ }^\circ\text{C}$) |
| T_s | Sky Temperature ($^\circ\text{C}$) |
| T_a | Ambient Temperature ($^\circ\text{C}$) |
| T_{gi} | Inner Glass cover Temperature ($^\circ\text{C}$) |
| T_{go} | Outer Glass cover Temperature ($^\circ\text{C}$) |
| T_v | Vapour Temperature ($^\circ\text{C}$) |
| T_{w1} | Temperature of upper water ($^\circ\text{C}$) |
| T_{p1} | Temperature of upper plate surface ($^\circ\text{C}$) |
| T_{p2} | Temperature of lower plate surface ($^\circ\text{C}$) |
| T_{w2} | Temperature of lower water ($^\circ\text{C}$) |
| T_i | Water Temperature at i ($^\circ\text{C}$) |
| T_g | Liner Temperature ($^\circ\text{C}$) |
| α_g | Absorptivity of glass (dimensionless) |
| H_1 | Fraction of energy absorbed by water (dimensionless) |
| η_2 | Fraction of energy absorbed by black plate (dimensionless) |
| L | Latent heat (J/Kg) |

- Conversion and Management, 2002, 43(13), 2469-2478.
10. Kumar S., Tiwari G.N. Estimation of convective mass transfer in solar distillation system. *Solar Energy*, 1996, 57, 459-464.
 11. Panchal H.N., Shah P.K. Performance Improvement of Solar stills via experimental Investigation. *Int J of Advanced design and Manufacturing Technology*, 2012, 5(5), 19-23.
 12. Panchal H.N., Shah P.K. Investigation on Solar stills having floating plates. *Int J of Energy and Environmental Engineering*, 2012, 3(3), 3-8.

7. References

1. Sakhivel M., Shanmugasundaram S. Effect of energy storage medium (black granite gravel) on the performance of solar still. *Int J of Energy Research*, 2008, 32, 68-82.
2. Kudish A.I., Gale J., Zarmi Y. A low cost design solar desalination unit. *Energy Conversion and Management*, 1982, 22, 69-74.
3. Cooper P.I. Digital simulation of transient solar still processes. *Solar Energy*, 1969, 12, 313-331.
4. Voropoulos K., Mathioulakis E., Belessiotis V. Experimental investigation of solar still coupled with solar collectors. *Desalination*, 2000, 138, 103-110.
5. Lawrence S.A. Theoretical evaluation of solar distillation under natural circulation with heat exchanger. *Energy Conversion and Management*, 1990, 30, 203-213.
6. Riffat S.A. Solar absorption system for water desalination. *Renewable Energy*, 1995, 15, 101-120.
7. Sharma V.B., Mullick S.C. Estimation of heat transfer coefficients the upward heat flow and evaporation in a solar still. *Transactions ASME, J of Solar Energy Engineering*, 1991, 113(1), 36-41.
8. Eiichi I. Enhanced boiling heat transfer of water/salt mixture in restricted space of the compact tube bundle. *Heat Transfer Eng*, 2001, 22(3), 4-10.
9. Zheng H., Zhang X., Zhang J., Wu Y. A group of improved heat and mass transfer correlations in the solar stills. *Energy*

