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Enhanced Performance of a Single Basin Double Slope Solar Still with Thin Film of Water Flowing over the Cover Plate

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Abstract

This paper presents the experimental investigation of single basin double slope solar still. The experiments were conducted in India using a double slope solar still with cover tilt angles ranging from 11˚ to 70˚. The optimum tilt angle was found to be 20˚ during the month of February. The still productivity was also compared with conventional single slope solar still of the same size and the effect of orientations like east-west and north-south on productivity. After fixing the orientation, effect of water depth was studied. The results show that distillate output decreased linearly with increasing water depth in the still. The effects of cooling water flow over the cover plate were studied. Flow rates in the range of 100ml/min to 1800 ml/min were considered and an optimum flow rate for production was found to be 250ml/min. The maximum distillate output of 3.98 L/Day/m^2 was obtained with minimum depth of 10mm of water in the basin and at an optimum flow of water flowing over the cover plate. The percentage increase in water production with cooling arrangement was 30.5%in comparison with double slope solar still without cooling. The economic analysis depicted a payback period of 288 days.

Keywords: Cover plate angle, solar still, orientation, water depth, water flow, desalination, productivity

1. Introduction

Clean potable water is a basic necessity for man along with food and air. Fresh water is also required for agricultural and industrials purposes. Direct use of water from sources like rivers, lakes, sea and underground water reservoirs are not advisable, because of the presence of higher amount of salt and harmful organism. The higher growth rate in world population and industries resulted in a large escalation of demand for fresh water. The natural sources can meet a limited demand and this leads to acute shortage of potable water.

The solar desalination technologies using solar still is the cheap and simple process [1]. A black painted basin contains brackish or sea water is enclosed in a completely air tight envelop formed by wooden frame and a transparent cover at top. The black basin absorbs the maximum portion of the transmitted radiation through the cover. Consequently, water contained in the basin gets heated up and evaporates in the saturated condition inside the still. Water vapor rises up until it comes in contact with the cooler inner surface of the cover plate. There, it condenses as pure water, slide down along the bottom surface of the cover plate due to gravity and is collected using a drain. The construction of this type of still is plausible by denizens in rural areas using the locally available materials.

The production capacity of a simple basin type solar still is very less. This makes the system highly uneconomical. Good number of work has been carried out by researchers, to improve the productivity of the still by adopting different techniques. Recently, the progresses in improving the effectiveness of the solar still have been studied by [2] K. Kalidasamurugavel et al. and was reported that water depth has significant effect on productivity of the basin. An investigation by M.R.Rajamanickam et al [3] shows that, the water depth is inversely proportional to the productivity of the still.

Around 11% of radiation received by the still basin is reflected back without being used [1]. The optimum inclination depends upon the location, glassing material and the seasons. They have also found that the glass should be at 10˚ inclination, in order to avoid back drop of the condensate. [4] G.N.Tiwari et al have optimized glass cover inclination for maximum yield in a solar still. [5] Bilal.A.Akash Mousa et al, conducted experimental studies on the basin type solar still under local climatic conditions and studied the effect of glass cover inclination, salinity and water depth. [6] M.Abd.Elkader et al studied the effect of base slope angle and glass cover angle, an investigation of the parameters involved in simple solar still with inclined yute. [7] G.N.Tiwari et al studied the transient performance of a single basin solar still with water flowing over the glass cover. The distillate production of the system is almost doubled by lowering the temperature of the glass cover by water flowing over it at a uniform velocity. [8] Sangeeta suneja et al analyzed the effect of water flow on internal heat transfer solar distillation. The evaporative heat transfer co-efficient decreased when the water depth in the basin was increased. [9] V.S.V.Bapeshwar rao et al studied the effect of water flowing over the upper glass cover of a double basin solar still on its transient performance and has done a comparative analysis of the double basin solar still with and without water flow over the upper glass cover. [10] Zeinab S.Abdel Rahim et al analyzed the experimental and theoretical study of a solar desalination system located in Cairo, to enhance the performance using solar parabolic trough with focal pipe and simple heat exchanger. The results show that fresh water productivity is increased by an average of 18%due to the modification. Improvement of the tilted wick solar still by using a flat plate reflector were analyzed Hiroshi Tanaka et al [11]. The external reflector can increase the distillate productivity in all but the summer seasons, and the increase in the daily amount of distillate averaged over the four days is predicted to be about 9%.

The objective of this work was on the single basin double slope solar still with and without cooling arrangement (1) to determine the cover plate angle. (2) The effect of depth of water in the still basin. (3) The effect of cooling water flow rate over the cover plate on still productivity, (4) Economic analysis of the optimized solar still with cooling arrangement.

2. Experimental Setup

Fig.1 shows the schematic of a solar still with a single basin double slope cover. The overall dimensions of the still are: length = 1m, breadth = 1m. Height = 0.15m, basin liner area = 1.0m^2 and the cover area = 1.2m^2. The setup comprised of a storage tank, basin, steel frame structure, glass cover, insulation, measuring jar, temperature measuring devices and piping. The black painted still basin made up of 18 gauge galvanized iron sheet, was placed inside the steel frame structure at a pre determined height. The area below the basin was filled with saw dust as insulating material. The outer basin is made up of mild steel sheet. The top is covered with two glasses of thickness 4mm, inclined at 20˚ on both sides, using a metal frame. The condensed water is collected in the v-shaped drain path provided below the glass cover edge on both sides. The condensate collected on both side of the still is continuously drained through flexible hose and stored in a measuring jar. The temperatures were measured using thermocouples. A hole is provided for water inlet. A small tube is inserted through the hole to supply raw water continuously to the basin from storage tank (T_1) through the valve (v_1). Thus the mass of water in the basin always kept constant.

Fig.2 shows the schematic arrangement of double slope solar still with cooling arrangement for cover plate. The cooling water flow rate considered in this study were 100, 200, 250, 300, 600, 900, 1200, 1500, and 1800ml/min. A separate tank (T_2) at a height of 1.5m above the ground level was installed to supply cooling water to cover plate through an aluminum pipe placed over the cover plate. The diameter of the aluminum pipe is 0.0127m and 24 holes drilled on the aluminum pipe of diameter 0.001m having the pitch of 0.04m. The flow rate was adjusted with help of vale (v_2) as shown in fig.2. The aluminum pipe and tank outlet pipe were connected through a flexible hose of diameter 0.01905m.

This experimental setup was designed, installed and tested in the Energy Laboratory, Department of Mechanical Engineering, Annamalai University, Annamalai Nagar, Tamil Nadu, India (Latitude 11˚North). The whole experimental setup was kept in the north-south orientation.

Copper Constantan thermocouple was used for temperature measurement. These thermocouples were fixed at still basin plate, water, inside and outside surface of the glass cover. Temperatures were measured at more than one location and the average was considered for the base plate temperature and basin water temperature. Thermocouples were integrated with a temperature indicator and selector switch. To measure the solar radiation a calibrated Eppley Pyranometer was used. The accuracies of various measuring instruments used in these experiments are given in table 1. The experiments were conducted during the months of February and March 2011. Hourly measurements were made for ambient temperature, and basin water temperature and glass cover temperature from 9.00am to 5.00pm during the trial period. These temperatures were measured with the aid of copper constantan thermocouples and noted from digital temperature indicator. The hourly weather data, i.e., solar radiation and wind speed were measured with the help of Eppley Pyranometer and anemometer. For, different orientations like east-west and north-south during clear sunshine hours, heat transfer co-efficient and instantaneous efficiency were estimated from collected data of DS solar still with and without water flow over the cover plate.

Table 1. Accuracies and ranges of measuring instruments

Sl. No.	Instrument	Accuracy	Range	% Error
1.	Thermocouple	± 1˚C	0-100°C	0.25%
2.	Eppley Pyranometer	± 1W/m^2	0-2800 W/m^2	0.25%
3.	Measuring beaker	± 10 ml	0-1000 ml	10%
4.	Anemometer	± 0.1 m/s	0-15 m/s	10%

3. Results and Discussions

Fig.3 shows the cumulative amounts of distillate collected for different cover tilt angles. Because of the location and the time of the year, the maximum value of 3050 ml/day/m^2 was obtained at an angle of 20˚ on 7th February 2011. When the cover tilt angle increased above 20˚ the gap between the basin and the glass cover is higher and the absorption and evaporation rate decreased. When the cover tilt angle decreased below 20˚ the condensed water particles falls down partly to the basin and decreased the productivity. This tilt angle was then used for all other experiments in order to determine other effects on the solar distillation.

The hourly variation of volumetric rate of distilled water produced for east-west and north-south orientation is depicted in fig.4. Fixing the still in north south orientation yielded higher production rate. As shown by fig.4 the production rate slowly increases as the day progresses because of warming up action of the still. The peak production rate was obtained at 1.00pm. Furthermore, after 1.00pm, it begins to decrease. It is also noted that the north side, which is exposed to lower amount of insolation, produces more distillate than the south side. This is due to the fact that the north side losses more heat and it is not exposed directly to sunlight, there by being cooler, so it condenses more water. Fig. 5 shows the hourly variation of cumulative volumetric production for the northern side, southern side and the combination. A greater amount of water is collected from the northern side than from the southern side.

The effect of water depth in the solar still is presented in fig.6. The distillate output decreased with increased water depth and an output rate of about 3050 ml/day has been observed at a depth of 0.01m. The optimal depth of 0.01m will produce more evaporation and condensation thus increased output rate compared to other depths that were considered.

Fig.7 shows the effect of cooling water flow rate above the cover plate on condensate output. Condensate output decreases with increasing cooling water flow rate from 250 ml/min. onwards. Also when the flow rate decreased below this value resulted in decreased distillate output because of non-uniform flow pattern over the cover glass thereby reducing the area of condensation. At this flow rate distillate output was maximum and flow distribution also uniform over the surface of the cover plate. The optimum flow rate of 250ml/min yielded the maximum yield of 3980ml/day.

Fig.8 presents the hourly variation of the solar intensity and ambient temperature of the experiments on 7th

February 2011 and 7th March2011. According to this figure the solar intensity values and ambient temperature staring from 9.00am gradually increases up to 1.00pm after 1.00pm gradually decreases up to 5.00pm. The peak values were obtained at 1.00pm and are 878.3573W/m^2 and 37˚C respectively.

Fig.9 presents the variation hourly temperatures for experiments conducted on the 7th day of March 2011 using a still kept at a tilt angle of 20˚. Similar trends were noticed for all experiments and the water temperature in the base of the still was always the highest among all the temperatures since the solar energy is absorbed there. The maximum water temperature always occurred between the hours of 1.00 to 2.00pm. It ranged between 61 and 64˚C. Ambient temperature was in the range or 33 to 37˚C

Fig.10 and Fig.11 shows the variation of water temperature, glass cover temperature and the difference between the water and glass cover temperature for without cooling and with cooling respectively. The temperature of water, glass and their differences gradually increase between 9.00am to 1.00pm for both cases still with cooling and still without cooling. After 1.00pm the temperature showed decreasing trend till 5.00pm. The temperature difference between the water and glass cover was found to be maximum for still with cooling arrangement compared to still without cooling arrangement. The maximum temperature difference was recorded as 13°C at 1.00pm in the case of still with cooling arrangement.

The hourly fresh water productivity is shown in fig.12 and fig.13. It is clear that highest distillate output was obtained from the still with cooling arrangement, due to the effect of the temperature difference between the water and glass cover increases.

Fig.14 shows the variation of convective, radiative and evaporative heat transfer coefficients for still with and without cooling arrangements. The heat transfer rate is higher for with cooling compared to without cooling for all the cases, due to the effect of the temperature difference between the water and glass cover. This is because of the fact that the heat transfer has direct relationship with temperature difference.

The hourly variation of instantaneous efficiency is shown in fig.15. The maximum efficiency was obtained for still with cooling compared to still without cooling arrangement. The peak values were obtained at 1.00pm in both the cases. The maximum difference is 25.42% at 1.00pm and the minimum difference is 1.44% at 9.00am

The present work revealed that the modified still with cooling arrangement and set at optimum angle and flow rate is an efficient one.

4. Economic Analysis

The payback period of the experimental setup depends on overall cost of fabrication, maintenance cost, operating cost and cost of feed water. The cost of feed water is negligible.

Overall fabrication cost to be considered	= Rs.10000 ($182)
Cost per litre of distilled water	= Rs.10 ($0.18)
Productivity of the solar still	= 3.98 l/m^2/day
Cost of water produced per day	= cost of water / litre X productivity
	= 10 x 3.98 = Rs.39.8 ($0.724)
Maintenance cost	= Rs.5/day ($0.09)
Net earnings	= Cost of water produced – maintenance cost
	= 39.8 – 5 = Rs.34.8 ($0.633)
Payback period	= Investment/Net earning
	=10000/34.8 = 288 days

5. Conclusions

Based on the results the following conclusions were drawn upon,

The optimal angle of the cover plate is 20˚ irrespective of the still with or without cooling.

The depth of water 0.01m in the still basin produced the highest distillate output rate of 3980 ml/day/m^2

compared to the other depths with cooling arrangement, the output rate at the depth of 0.01m was 3050 ml/day/m^2 still without cooling arrangement.

The cooling water flow rate of 250 ml/min over the optimized cover plate angle of 20˚ at the optimized depth of water 0.01m in the still basin increased the overall productivity by 30.50%.

The optimized solar still was economically analyzed and the payback period was determined to be 288 days.

Acknowledgements

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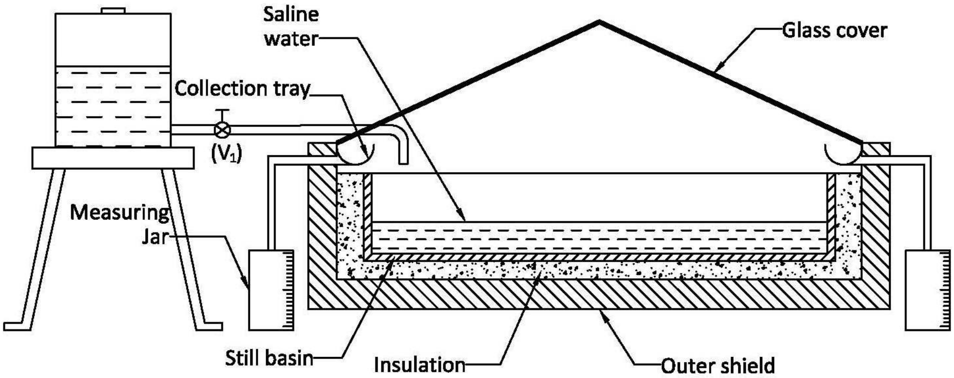

Figure 1. Schematic arrangement of double slope solar still

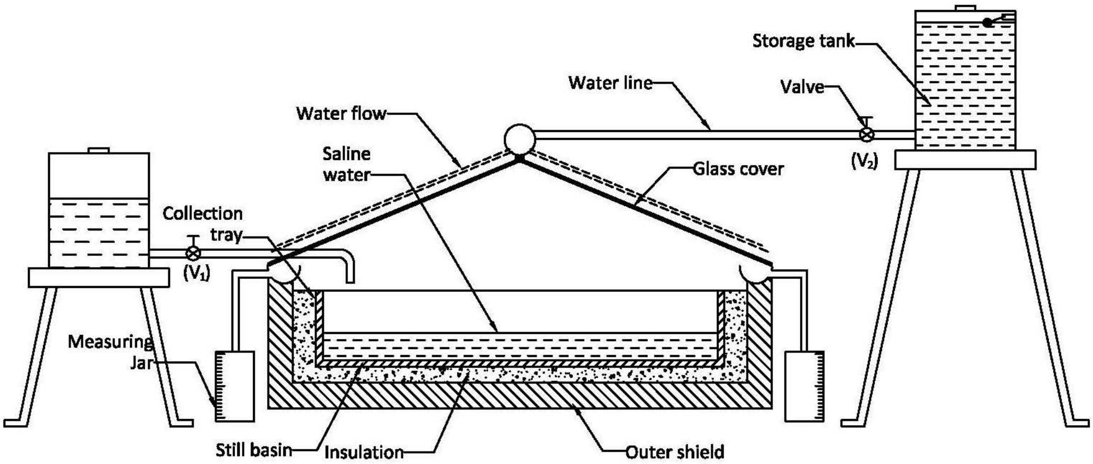

Figure 2. Schematic arrangement of double slope solar still with water flowing over the cover plate

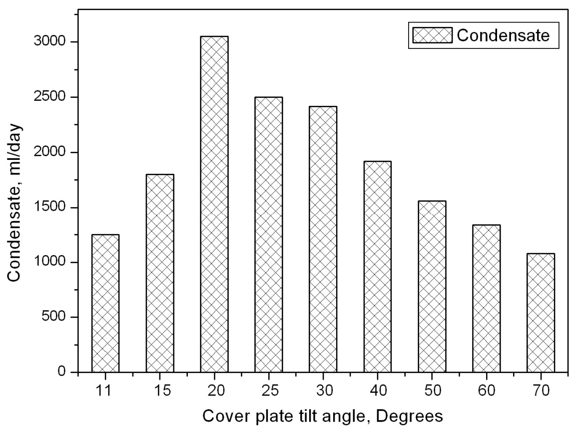

Figure 3. The effect of cover plate tilt angle on production of distillates

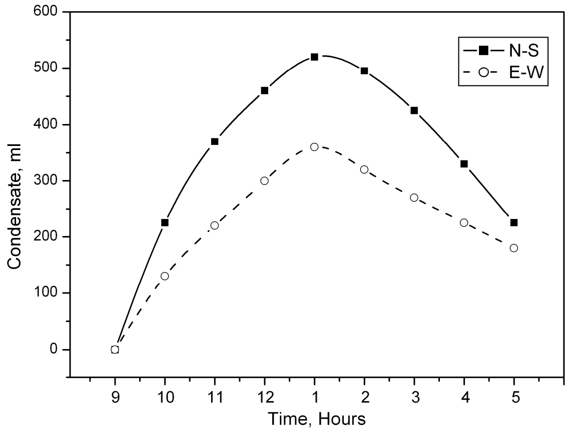

Figure 4. The effect of orientations on production of distillates

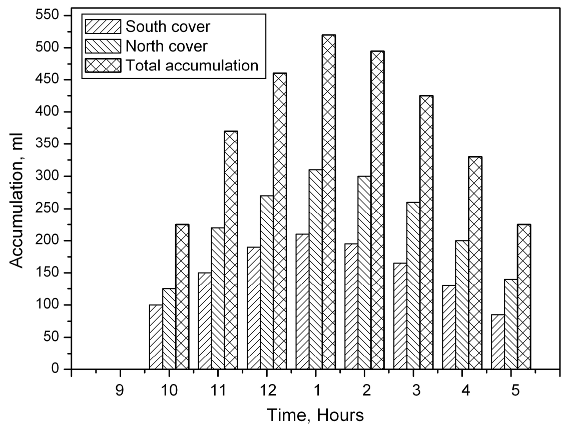

Figure 5. Cumulative volumetric production as a function of the hour of the day

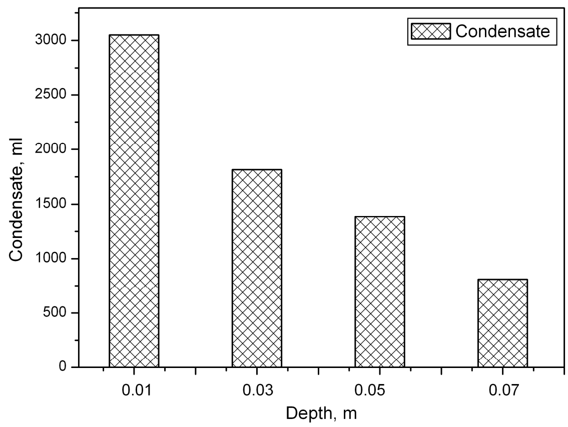

Figure 6. Effect of water depth on production of distillates

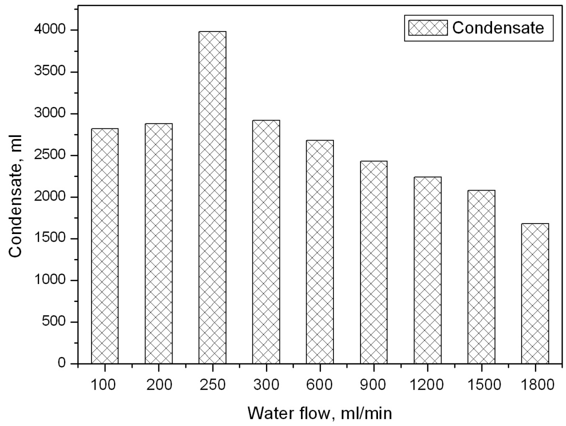

Figure 7. Effect of water flow over the cover plate on production of distillates

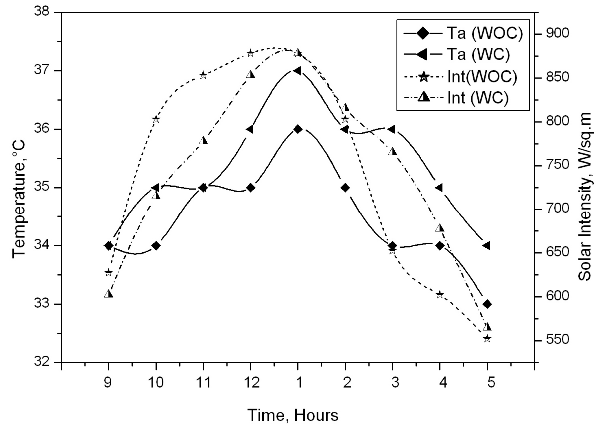

Figure 8. Hourly variation of solar intensity and ambient air temperature

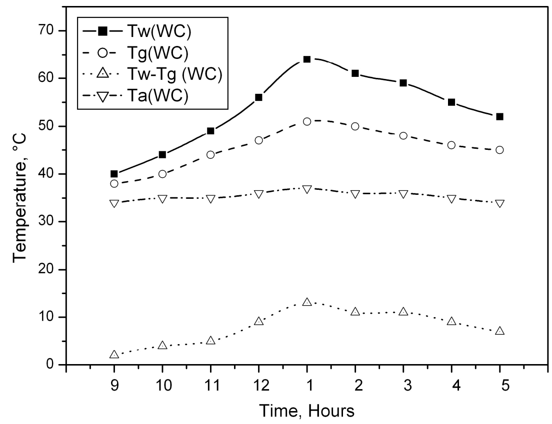

Figure 9. Hourly variation of temperatures for experiments conducted on the 7th of March for with cooling arrangement

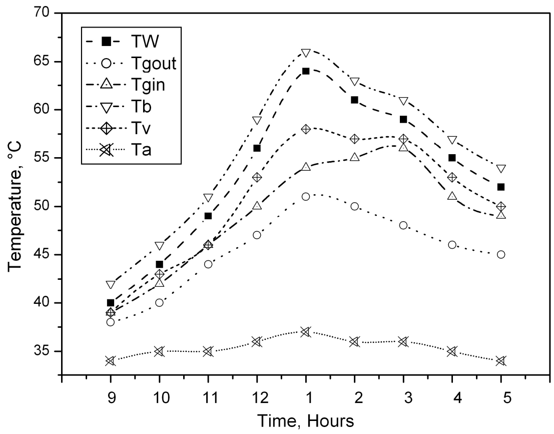

Figure 10. Hourly variation of water, glass cover, water and glass cover and ambient temperatures for with cooling arrangement

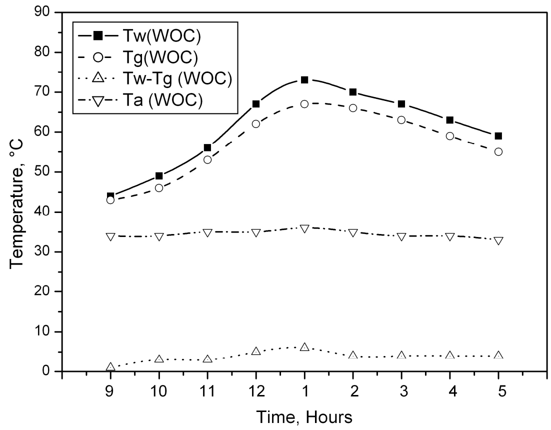

Figure 11. Hourly variation of water, glass cover, water and glass cover and ambient temperatures for without cooling arrangement

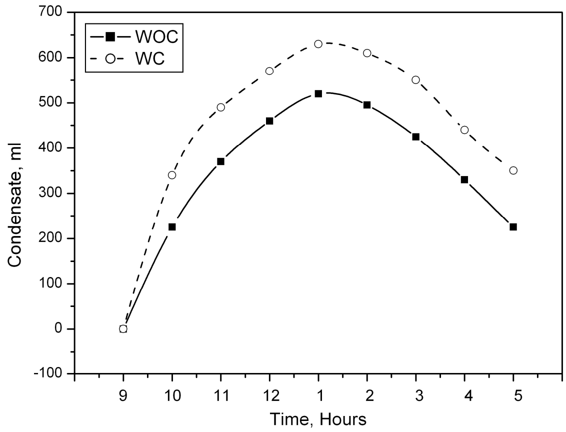

Figure 12. Hourly variation of fresh water productivity for without cooling and with cooling arrangement

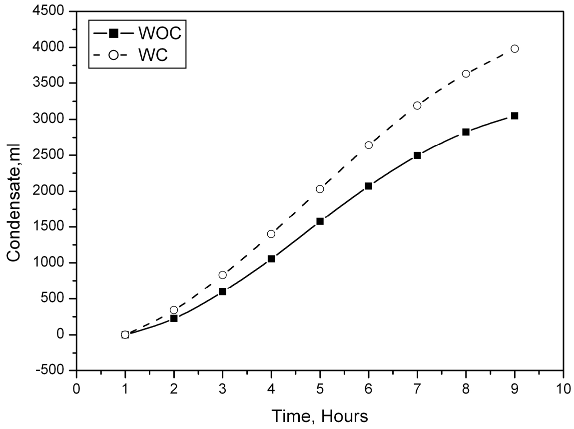

Figure 13. Hourly variation of accumulative fresh water productivity for without cooling and with cooling arrangement

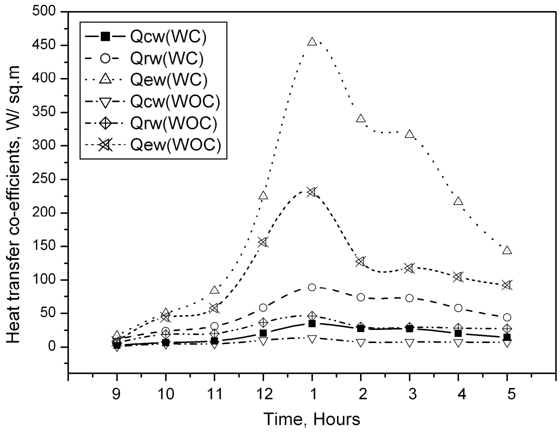

Figure 14. Hourly variation of radiative, convective and evaporative heat transfer co-efficient for without cooling and with cooling arrangement

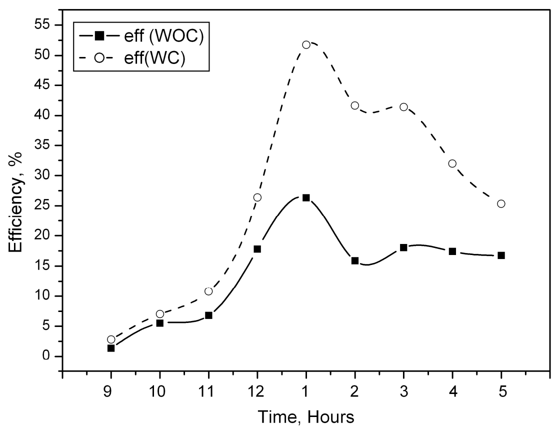

Figure 15. Hourly variation for instantaneous efficiency for without cooling and with cooling arrangement

Nomenclature

A_C	Area of cover, m^2
A_s	Area of basin liner, m^2
h_{cw}	Convective heat transfer coefficient from water to cover, W/ m^2 °C
h_{rw}	Radiative heat transfer coefficient from water to cover, W/ m^2 °C
h_{ew}	Evaporative heat transfer coefficient from water to cover, W/ m^2 °C
I(t)	Total solar radiation, W/ m^2
P_g	Partial pressure at cover temperature, N/m^2
P_w	Partial pressure at basin water temperature, N/m^2
q_{cw}	Convective heat transfer from water to cover, W/ m^2
q_{rw}	Radiative heat transfer from water to cover, W/ m^2
q_{ew}	Evaporative heat transfer from water to cover, W/ m^2
T_a	Ambient temperature, °C
T_g	Glass cover temperature, °C
T_w	Basin water temperature, °C
V	Wind speed, m/sec
WOC	Without cooling
WC	With cooling
ε_{eff}	Effective emissivity, dimensionless
ε_g	Emissivity of cover, dimensionless
ε_w	Emissivity of water, dimensionless
σ	Stefan-Boltzmann constant, W/m^2 K^4
η	Instantaneous efficiency, %

Appendix

Various relations for heat transfer co-efficient, heat transfer rate and for partial vapor pressure are [2] and [12]

$P_w = 7235 - 431.43\,T_w + 10.76\,T_w^2$

$P_g = 7235 - 431.43\,T_g + 10.76\,T_g^2$

$$h_{cw} = 0.884\left[\left(T_w - T_g\right) + \frac{(P_w - P_g)(T_w + 273)}{(268.9\times 10^{-3} - P_w)}\right]^{\frac{1}{3}}$$

$q_{cw} = h_{cw}\,(T_w - T_g)$

$$h_{rw} = \varepsilon_{eff}.\ \sigma\left[(T_w + 273)^2 + \left(T_g + 273\right)^2\right]\cdot\left[T_w + T_g + 546\right]$$

$\sigma = 5.669 \times 10^{-8}\,W/m^2K^4$

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1\right]^{-1}$$

$\varepsilon_g = \varepsilon_w = 0.9$

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

$$h_{ew} = 16.273 \times 10^{-3} \times \frac{h_{cw}(P_w - P_g)}{(T_w - T_g)}$$

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

$$.\eta_{instantaneous} = \frac{h_{ew}(Tw - Tg)}{I(st)}$$