

Parametric Study of Solar Energy Desalination System

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Abstract-- The quality of life and population expansion makes the average of water consumption to be very high, also the operating cost of the customary methods of desalination processes are so expensive and hostile relative to the surrounding. Therefore, it is very important to find clean, inexpensive, recent and simple methods for producing potable water like solar energy desalination systems. To improve the performance of a solar still, the effect of operating variables like solar intensity, wind velocity

and designing variables such as water depth in the basin and solar still direction, on the water productivity was studied and then discussed. It can be concluded that the maximum productivity of water has been achieved when the water depth in the basin is at least Also, it can be seen that the best direction of the still was towards the east-south during the June month in Basrah city.

SYMBOLS

A_{evc}	The collector area	m^2
A_b	Area of basin still	m^2
D_2	Inner Diameter of the evacuated tube	m
h_{cw}	Convective heat transfer coefficient from water	$\text{W}/\text{m}^2 \cdot ^\circ\text{C}$
h_{ew}	Evaporative heat transfer coefficient from water	$\text{W}/\text{m}^2 \cdot ^\circ\text{C}$
h_{rw}	Radiative heat transfer coefficient from water	$\text{W}/\text{m}^2 \cdot ^\circ\text{C}$
I	Solar intensity	$\text{W}/\text{m}^2\text{hr}$
L_{evc}	Length of evacuated tube	m
$\dot{m}$	Mass flow rate of water transfer in the collector	kg/s
M_w	Amount of the water productivity	$\text{kg} / \text{m}^2 \text{hr}$
N	Number of evacuated tubes	
p_g	partial vapour pressure at glass temperature	$\text{N}.\text{m}^2$
P_w	Partial vapour pressure at water temperature	$\text{N}.\text{m}^2$
q_{evc}	Heat transfer of water through the evacuated tube	W/m^2
q_{cw}	Heat transfer from water by convection	W/m^2
q_{ew}	Evaporative heat transfer	W/m^2
q_{rw}	Radiative heat transfer from water	W/m^2
t	Time	hr.
T_a	Air Temperature	$^\circ\text{C}$
T_g	Glass Temperature	$^\circ\text{C}$
T_w	water temperature	$^\circ\text{C}$
T_{out}	Outlet temperature of the collector	$^\circ\text{C}$
V	Velocity of the air	m/s

Greek Symbols

ϵ_{eff}	Effective emissivity
ϵ_w	Water emissivity
ϵ_g	Glass emissivity
η	Thermal efficiency
σ	Stefan-Boltzmann's constant (5.6697×10^{-8})

Subscripts

b	basin	r	radiation
g	glass	c	convection
w	water	e	evaporative
evc	evacuated tube		

2- INTRODUCTION

Desalination processes require significant amounts of energy. Due to the high cost of conventional energy sources, which are also environmentally harmful. Renewable energy

sources particularly solar energy, have gained more attraction, since their use in the desalination plants will save conventional energy for other applications, and reduce the environmental pollution, [1].

Desalination is now successfully practiced in many countries of the Middle East, North Africa, southern and western US, and southern Europe to meet the industrial and domestic water demands, [2]. **Singh et al.** [3] studied a Solar still integrated with a parabolic concentrator, evacuated tube collector (ETC) and flat plate collectors (FPC) that have been tried by various scientists to enhance the daily yield. The flat plate collector is popular due to its low maintenance cost and simple design. However, the FPC have two major drawbacks: (i) convection heat loss from the collector plate to the glass cover and (ii) the absence of sun tracking. On the other hand, an ETC overcomes both of these drawbacks due to the presence of vacuum in the annular space between two concentric glass tubes, which eliminates much of the necessity for sun tracking by its tubular design. However, **Kim et al.** [4] have found a significant increase in the outlet temperature of water and a thermal efficiency (more than 14.94%) of ETC by using a tracking mechanism in comparison with that of stationary ETC. The natural circulation is a most interesting technology used for solar energy exploitation due to its simplicity and low maintenance compared with the system using an auxiliary pump. However, the thermosyphon principle results in a slow circulation rate and this renders the system less effective. The limitation of ETC is that it can only be used for a low-pressure system, as the tubes can only withstand a few meters of water head. The present study has focused on the thermal modeling and performance evaluation of a solar still integrated with an evacuated tube collector in a natural mode. The effect of water

depth in the solar still basin on the yield, energy and exergy efficiencies has been estimated. The system has been optimized to find the best combination between the size of (ETC) and water depth in the solar still for an optimum performance. **Sadiq (2014)** [5], presented a study for evaluating the performance of an active double slope solar still using heating pipes evacuated tubes theoretically, and compared it with the experimental results relative to Basrah city climate. The system consisted of solar still basin with an area of (1m²) connected to eight evacuated tubes. He also studied the effect of solar intensity, wind velocity and evacuated tubes on the water productivity. His tests have been extended from January to August 2013. He concluded that the solar still productivity has increased with increasing solar intensity and wind speed. The highest productivity of the system had about 11.23 kg for the period between 8:00 AM to 17:00 PM while the thermal efficiency of the system for the same period was 16.44% and showed that the water productivity values have increased by about 43.35% compared with those of the conventional solar system.

3- THEORETICAL ANALYSIS FOR THE SOLAR STILL
In this part, a whole mathematical model that depicts the processes in the basin of the solar still is offered. These models will help in calculating the hourly saturated vapor pressures of glass and water, the convective and evaporative losses coefficients from the water surface to the glass, the distillate output and the instantaneous efficiency of the still.

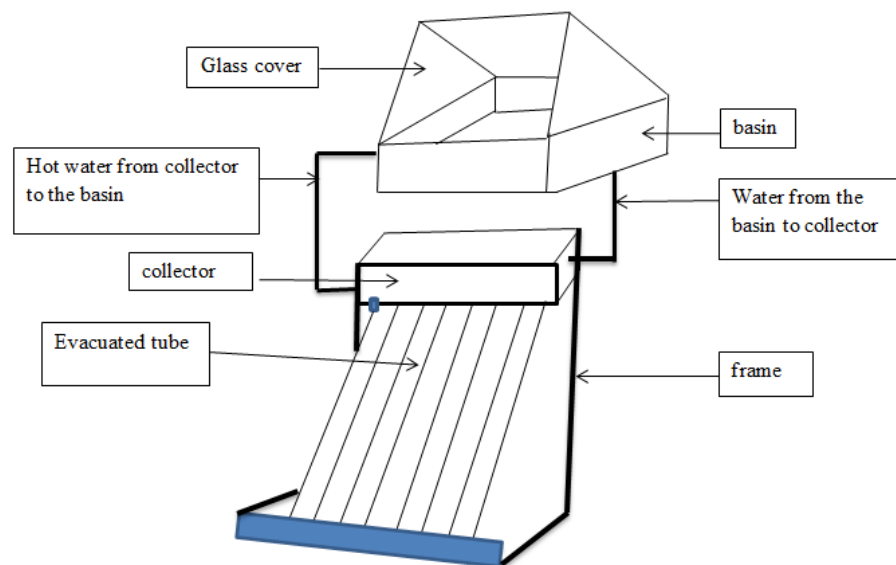


Fig. 1. The solar still with evacuated tube.

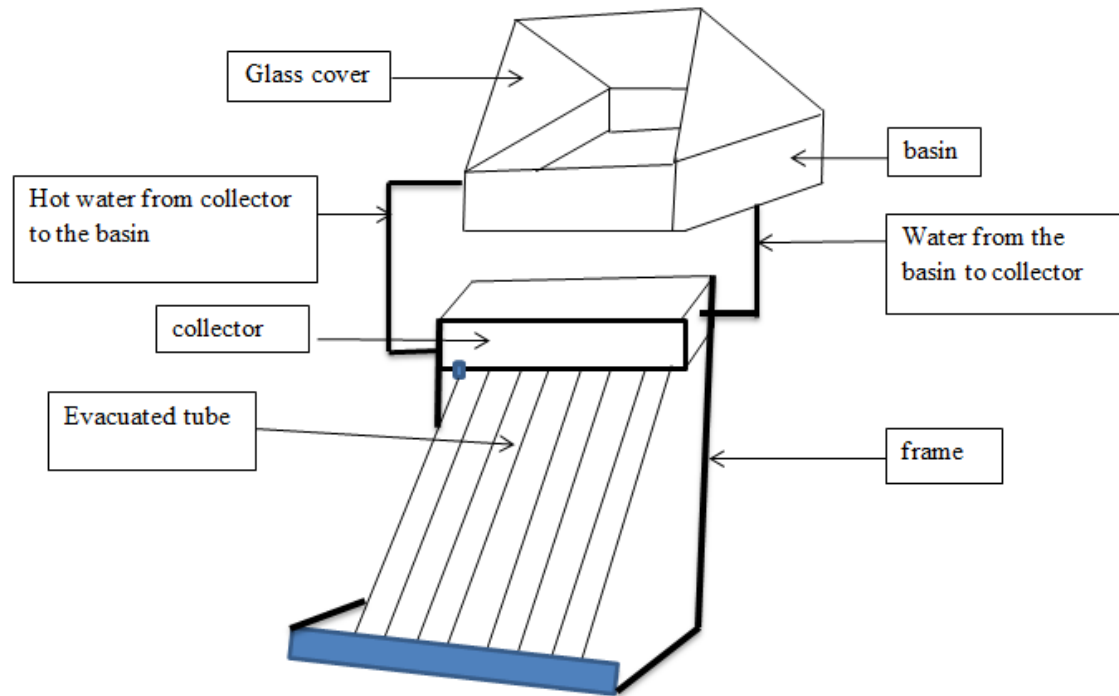


Fig. 1. The solar still with evacuated tube.

3-1 Internal heat transfer

The internal heat transfer mode, i.e. the heat exchange from the water surface to the glass cover inside the still unit is governed by radiation, convection and evaporation as follows [6]:

3-1.1 Radiation heat transfer

It is known that radiation heat transfer occurs between any two bodies when there is a temperature difference between them, and considering the water surface and glass cover, the radiation between water and glass can be given by, [3]:

$$q_{rw} = h_{rw}(T_w - T_g) \quad (1)$$

Where h_{rw} can be obtained from equation [7]

$$h_{rw} = \sigma \epsilon_{eff} [(T_w^2 + T_g^2)(T_w + T_g)] \quad (2)$$

Where:

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

ϵ_{eff} is the effective emittance between the water surface and glass cover, which can be presented by, [7]:

$$\epsilon_{eff} = \frac{1}{\left(\frac{1}{\epsilon_w} + \frac{1}{\epsilon_g} - 1\right)} \quad (3)$$

The values of the constants will be $\epsilon_w = 0.96$, $\epsilon_g = 0.88$ [7]

3-1.2 Convection heat transfer

Free convection occurs through the wet air in the enclosure because of the temperature difference between glass cover and the water surface. The convective heat transfer rate can be produced from the following equation:

$$q_{cw} = h_{cw}(T_w - T_g) \quad (4)$$

Where: h_{cw} is the convection heat transfer coefficient which is given by, [9]:

$$h_{cw} = 0.88^3 \sqrt{[T_w - T_g + \frac{(p_w - p_g)T_w}{268900 - p_w}]} \quad (5)$$

Where: p_g and p_w are pressures of the vapor at the glass cover and water temperatures respectively. They can be obtained from the following equations [9]:

$$p_g = e^{(25.317 - \frac{5144}{T_g + 273})} \quad (6)$$

$$p_w = e^{(25.317 - \frac{5144}{T_w + 273})} \quad (7)$$

3-1.3 Evaporative heat transfer:

Because of the condensation of the rising steam on the glass cover, there is heat loss by vaporization between the water surface and the glass cover. This can be obtained from the following equation:

$$q_{ew} = h_{ew}(T_w - T_g) \quad (8)$$

Where:

$$h_{ew} = 0.016273 h_{cw} \left(\frac{p_w - p_g}{T_w - T_g} \right) \quad (9)$$

3-2 Theoretical analysis of the manifold

The manifold part can be considered as a collector storage for heat in the solar still system, where the heat transferred from the heads of copper pipes to the heads of manifold to warm the water coming from the still basin at T_{in} . The hot water leaves the manifold at T_{out} .

The heat transfer of water through the evacuated tubes (q_{evc}) can be calculated from:

$$q_{evc} = m \cdot c_p (T_{out} - T_{in}) \quad (10)$$

The hourly-distilled water productivity of solar still is, [5]:

$$M_w = \left(\frac{q_{ew} + q_{evc}}{L} \right) * 3600 \quad (11)$$

Where, L : is the latent heat of water evaporation (J/kg),

The correlation for latent heat of water evaporation is calculated by, [12]:

$$L = [2501.897149 - (2.407064037 * T_w) + (1.192217 * 10^{-3} * T_w^2) - (1.5863 * 10^{-5} * T_w^3)] \times 1000. \quad (12)$$

The thermal efficiency of the whole system can be calculated by the following equation, [11]:

$$\eta = \frac{\sum_{i=1}^{10} M_w * L}{\sum_{i=1}^{10} (I * A_c * 3600) + (I * A_b * 3600)} * 10 \quad (13)$$

Where:

A_b is area of the basin still which is 0.25 m².

A_{evc} is the half area of the collector.

$$A_{\text{evc}} = 0.5 * \pi * N * D_2 * L_{\text{evc}} \quad (14)$$

Where:

N is the number of tubes which is 4.

D_2 is the diameter of the tube which is 0.058 m.

L_{evc} is the length of the tube which is 1.8 m.

4- SYSTEM DESCRIPTION AND EXPERIMENTAL STEPS

The experimental work includes constructing three solar still systems, which are similar in structure, shape and dimensions. Each system composes of a double slope solar still used to realise the maximum amount of solar radiation. The area of basin was 0.25m^2 (0.5m long, 0.5m wide). It is provided in each side with a channel which slopes from the ends to the center for collecting the distilled water output. The basin was made from fiber glass material that has small thermal conductivity to reduce the thermal losses, and there is a hole in the middle of the basin used to deliver the brackish water to the manifold of the evacuated tubes. Glass panes of 3 mm thickness are used as covers for the still, the slope of glass covers was taken as 30° to the horizontal. Also, there are four heating pipe evacuated tubes used in each system, these tubes are used to increase the temperature of brackish water in the basin which lead to increase water productivity. Each evacuated tube consists of two glass tubes made from extremely strong borosilicate glass, the ends of the tubes are connected to the copper headers which are fused together. On the internal surface of the inner borosilicate glass tube there is a black absorber plate. The heat is transmitted to the copper pipe and then collected in the head of the copper pipe which contacts with the manifold. The length of these tubes is 1.8 m, the outer and inner diameters are 0.058 m and 0.047 m respectively, and the length of the copper pipe is 1.3 m, the end bottom of the evacuated tube contains a predictive cap made from silicone rubber to resist the high heat. The manifold part is connected with the still basin and the head of copper pipes of the evacuated tubes make the system circular. The saline water flows from the still to the manifold as a warm liquid and comeback to the still basin as a hot water. The pipe of the manifold is made from copper and it contains 4 holes to the heads of copper pipes of evacuated tube. Figure (2) shows the whole system of the work of solar still with all parts and connections.



Fig. 2. shows the system of the work of solar still

Experimental work presented deals with the studying of two cases:

- 1- The first case dealt with studying the effect of water level in the basin on the water productivity where the water level in the basin for state1, state2 and state3 was 1, 2.5 and 4 cm respectively, by considering that the other parameters as constant (such as the direction of stills, solar radiation, wind speed, tilt angle and number of evacuated tubes) for all states.

- 2- The second case dealt with studying the effect of the still direction on the water productivity where the directions of states 1, 2 and 3 were east, south-east, and south respectively by considering that the other parameters as constant (such as the level of the water in the basin, solar radiation, wind speed, tilt angle of evacuated tubes and number of evacuated tubes) for all states.

5- RESULTS AND DISCUSSION

The experimental work was used for verifying the effect of operating and designing parameters like solar intensity, air speed, water level in the basin and direction of the solar still on the performance of solar still with evacuated tubes collector.

5-1 Effect of water level in the basin (first case)

The effect of water level in the basin on the water productivity in the solar still has been studied and discussed during May 2015. The depths of water in the basin for states 1, 2, and 3 were 1, 2.5 and 4 cm respectively. Also, the other design parameters were considered as constants for all the states. The amounts of water productivity from the state 1 during July 2015 were recorded as shown in figure (3). The amounts of water productivity from the solar still have fluctuated during the period due to the intensity of solar radiation, air temperature and wind velocity. These parameters were variable from time to time through the month of May, as well as, the appearance of some clouds in the sky during some days, which affected water productivity. From figure (3) it can be noticed that the highest productivity was on the 21st of July.

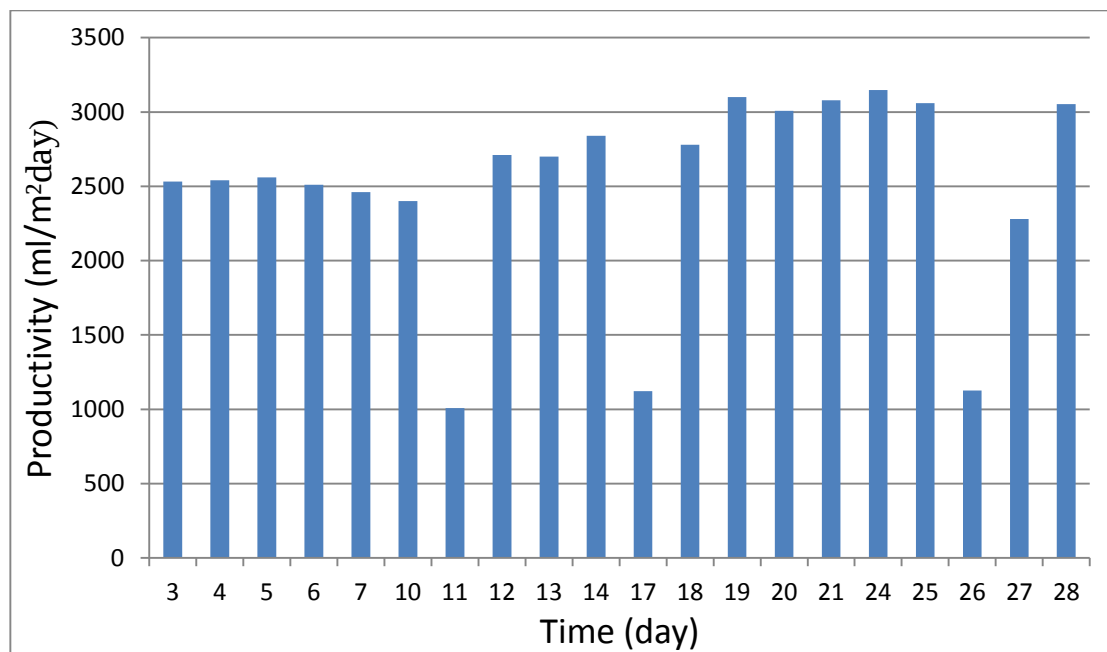


Fig. 3. Water productivity during the period between 3rd-28th of May 2015 for state 1.

Figure (4) shows the experimental results of water productivity for all the states during the period between 8:00 AM to 17:00 PM on the 24th of May 2015. The water productivity was inversely proportional with the water level in the basin.

The daily production for the states 1, 2 and 3 (from 8:00 AM to 17:00 PM) were 3148, 2976 and 2644 ml/m² respectively. During the early hours of the day until 14:30 PM the water productivity for state 1 was larger than those for states 2 and 3. This is due to the rate of heating for basin water with low level that is faster than the high level. Then, the difference in temperatures between water and glass cover has increased, so the amount of the vaporized water has increased too. After 14:30 PM where the solar intensity decreased, the amount of water productivity of state 3 was larger than those for the state 2 and 1 due to the water in state 3 having high heat capacity. Therefore, its water temperature has decreased slowly, but the daily yield for the first state is larger. Previously it was concluded that the distilled water productivity was inversely proportional with water level in the basin, where the distilled water productivity increased when the level of water in the basin has decreased.

The average thermal efficiencies were about 25.23%, 25% and 22% respectively, as shown in figure (5). The enhancement percentage of daily productivity due to the decrease of water depth in the basin from 4 cm to 1 cm was about 18%.

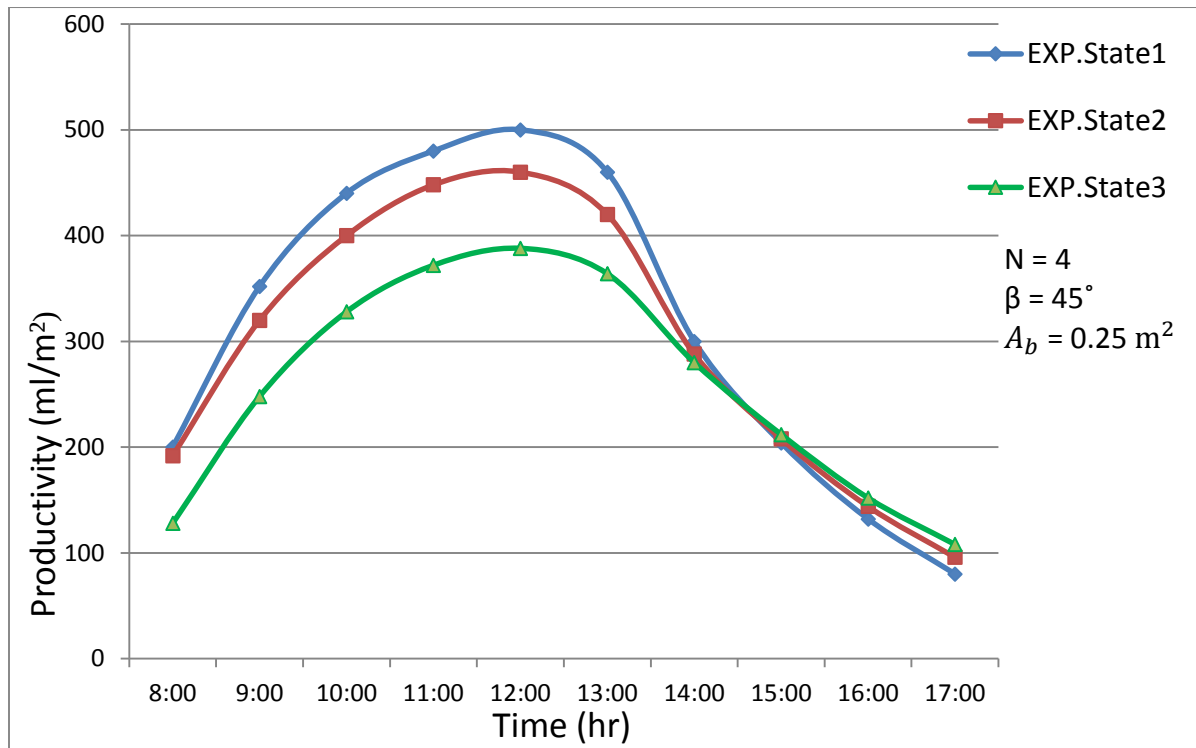


Fig. 4. Productivity as a function of time on the 24th of May 2015 for all the states.

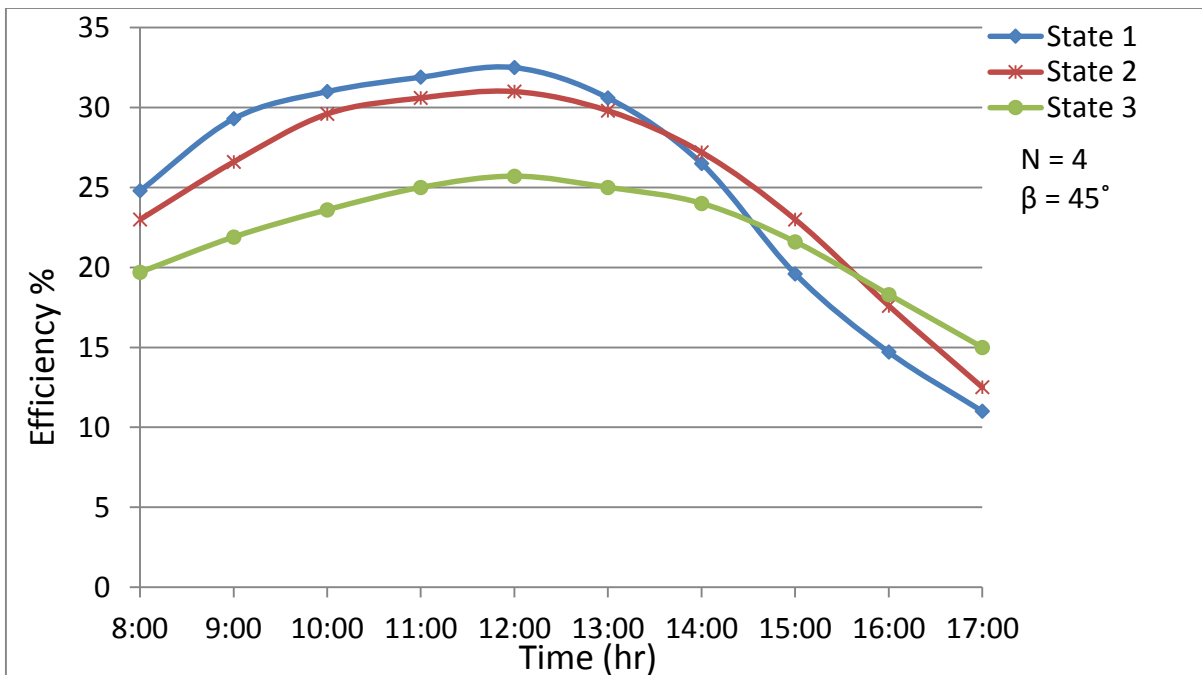


Fig. 5. Efficiency as a function of time on the 24th of May 2015 For all the states.

To check the accuracy of the results for the theoretical model, values of the measuring parameters like solar intensity, air speed and the temperatures of air, glass and water have been inserted in a computer program to calculate the theoretical results and compare them with the experimental data for all states 1, 2 and 3. The degree of agreement between them is summarized in the figures (6), (7) and (8) and table (1). The differences between the experimental

and theoretical values due to the heat losses from the basin and the fluctuations of the hourly climate parameters, e.g. solar intensity and air velocity as well as the loss of an amount of distilled water inside the basin. However, the degrees of agreement between theoretical and experimental results were about 85%, 83.7% and 82% for the states 1, 2 and 3 respectively.

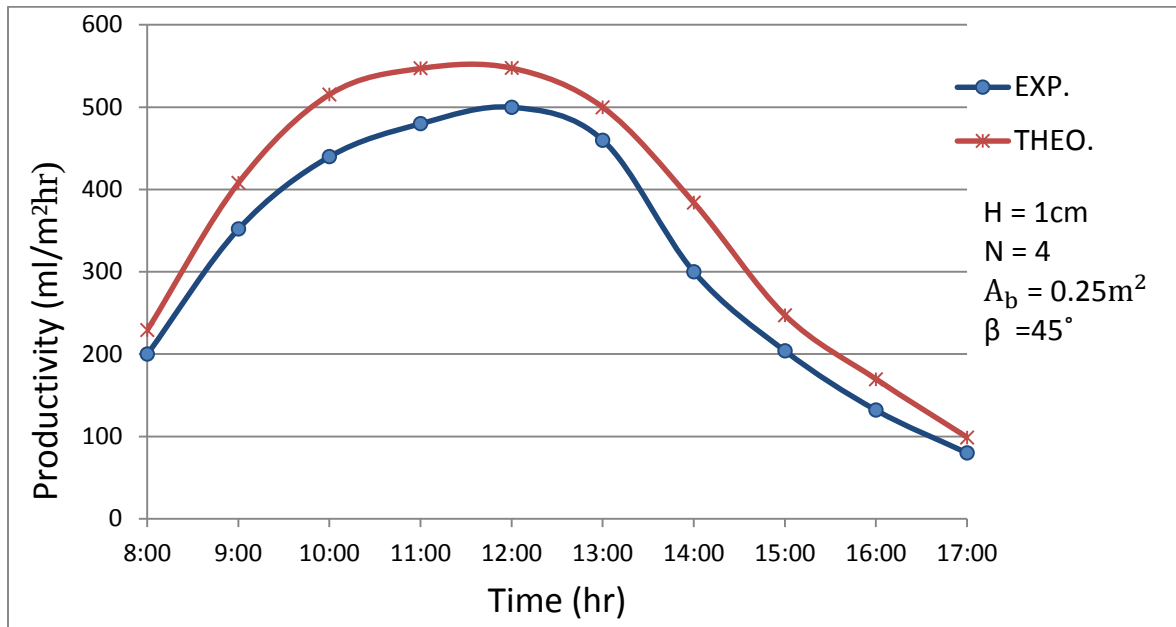


Fig. 6. A comparison between theoretical and experimental results of water productivity for 1CS1.

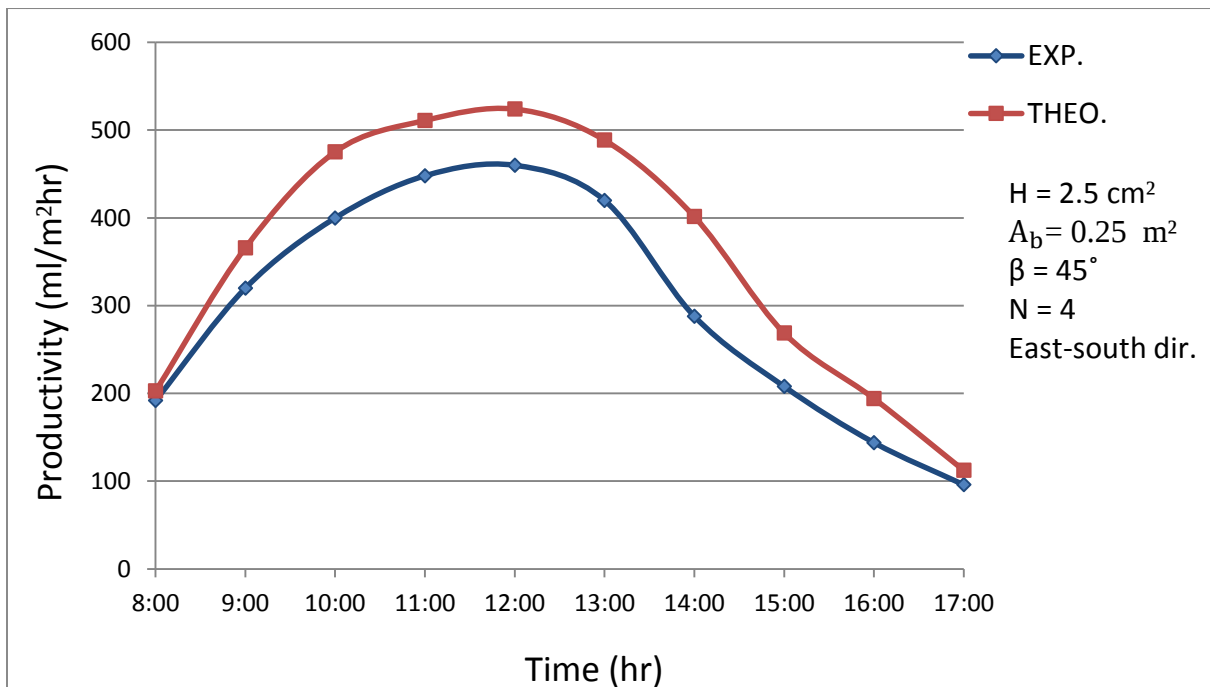


Fig. 7. A comparisons between theoretical and experimental water productivity values for 1CS2.

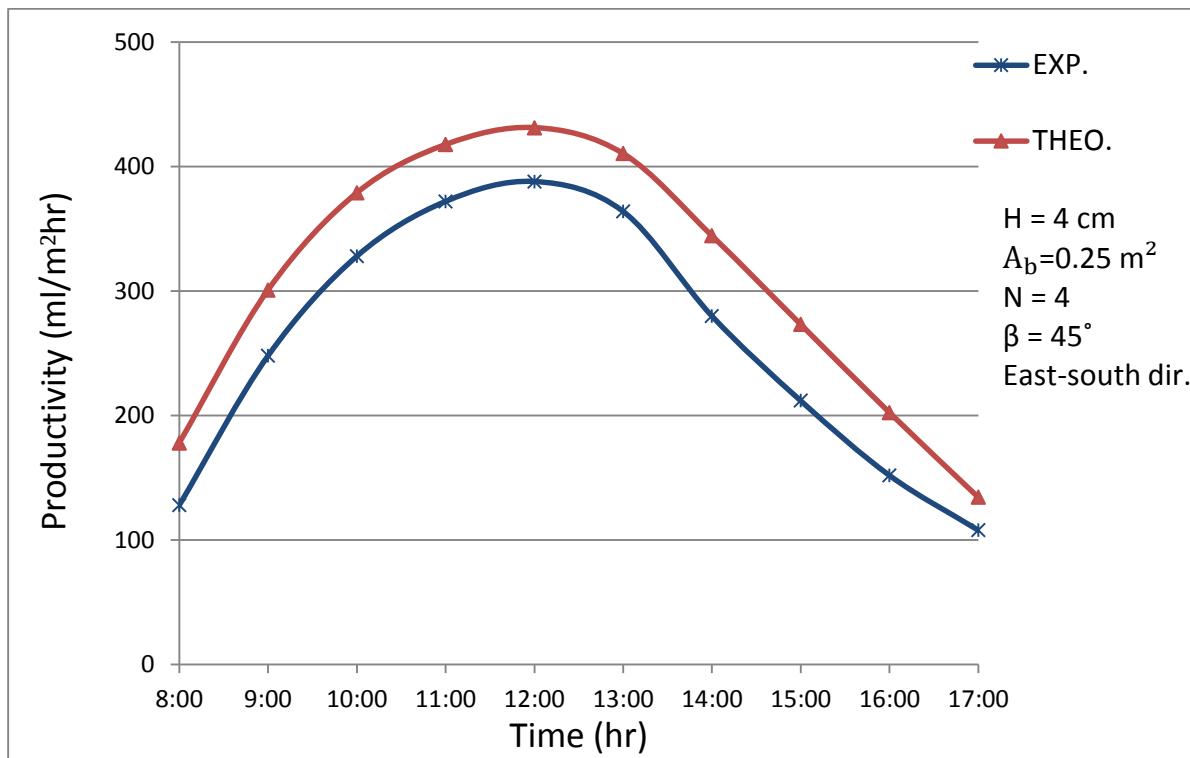


Fig. 8. A comparison between theoretical and experimental water productivity results of for 1CS3.

Table I
Degrees of agreement between theoretical and experimental results for all models of the first case.

State No.	Degree of agreement (%)
1CS1	85
1CS2	83.7
1CS3	82

5-1.1 Effect of operating variables on the water productivity

The effect of operating variables like solar intensity, air speed and temperatures of water, glass cover and outlet water from the collector, on the water productivity have been presented and discussed. The recording data have been measured on the 24th of May 2015.

The solar intensity has been measured and recorded as in figure (9) and its effects on water productivity of the solar still have been studied and discussed. Values of the solar still productivity have been recorded as shown in table (2) for the period between 8:00AM and 17:00PM. The results in table (2) show that the water productivity for all states increase gradually during the period between 8:00 AM to 12:00 AM. Where, it has reached maximum value at 12:00 AM because of the increasing

solar intensity from 587 W/m²hr to a maximum value of about 1100 W/m²hr during the period between 8:00 AM to 12:00 AM. These values have contributed to increase the amount of water produced inside the basin of the still. Then the water productivity decreased with time during the period after 12:00 AM because of the decreasing solar intensity.

Figure (10) and table (2) show that the air velocity has increased gradually from 1.5 m/s at 8:00AM to its maximum value of 2.9 m/s at 12:00AM, then it started decreasing after this period, until it reached 1.4 m/s at 17:00 PM. The air velocity has contributed to increase the value of water productivity. However, whenever air velocity increased, the air and glass temperatures decreased, and these lead to increase the amount of condensing water vapor.

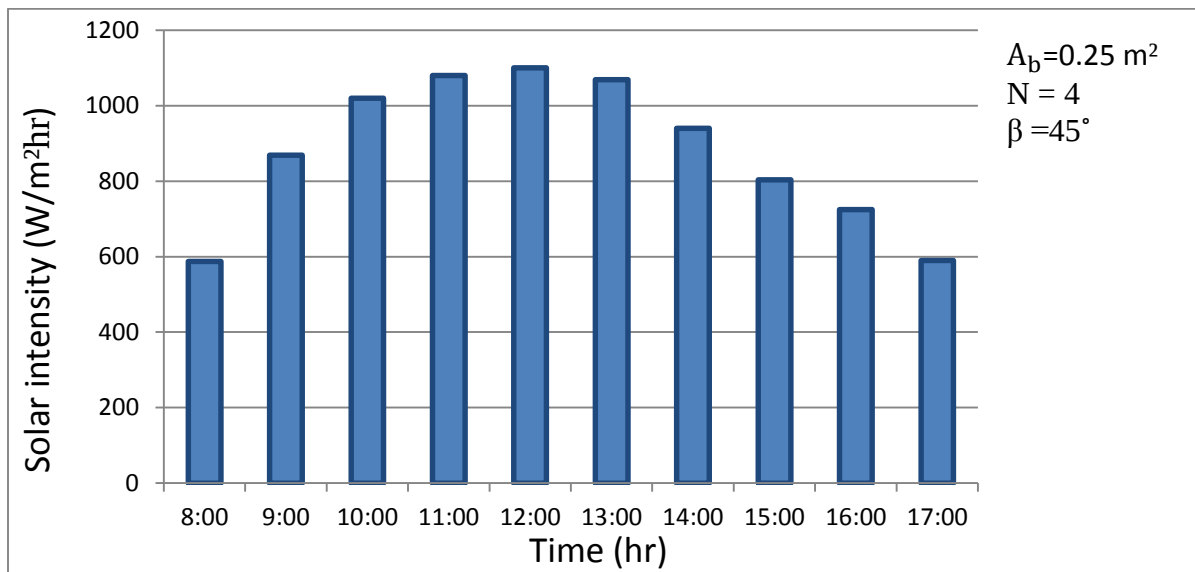
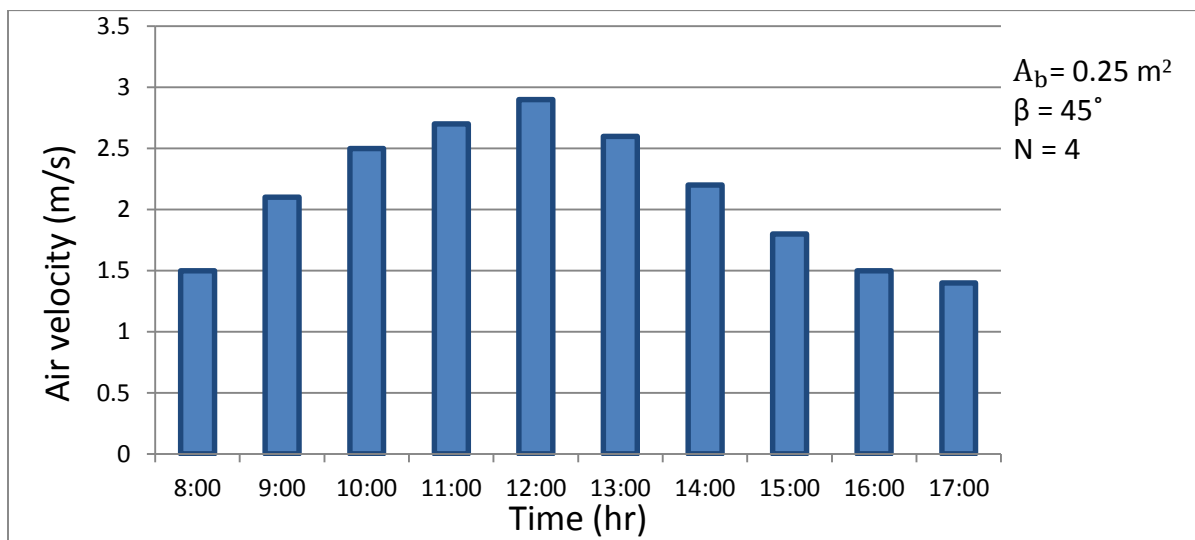
Fig. 9. Solar intensity as a function of time on the 24th of May 2015.Fig. 10. Air velocity as a function of time on the 24th of May 2015.

Table II
Solar intensity, wind velocity and water productivity for all states as a function of time on the 24th of May 2015.

Time (hr.)	Solar intensity (W/m²hr)	Wind velocity (m/s)	State 1 Temperatures (°C)			State 2 Temperatures (°C)			State 3 Temperatures (°C)		
			T _w	T _g	T _{out}	T _w	T _g	T _{out}	T _w	T _g	T _{out}
08:00	587	1.5	40	33.2	96	38.8	33	94	37.6	33	92
09:00	869	2.1	49.5	38.2	99	48.4	38	98	45.9	37	96
10:00	1020	2.5	55.9	44.5	100	54.2	43	100	50.8	41	99
11:00	1080	2.7	59.3	48.7	101	56.7	45.8	101	55.2	46	100

12:00	1100	2.9	60.3	50.2	101	58.6	48.3	101	57.1	48.3	101
13:00	1069	2.6	59.5	50	101	58	48.2	101	56.5	48	101
14:00	940	2.2	57	49.3	99	56	47.5	100	55.1	47.8	100
15:00	804	1.8	54	49	95	53	47.2	98	53.3	47.5	99
16:00	725	1.5	50.5	47.1	88	51	46.8	91	51.5	47.2	93
17:00	590	1.4	48	46	76	48.5	46.1	78	49.4	46.4	81

5-2 Effect of the solar still direction on water productivity (second case)

In the second case (2C) the effect of solar still direction on water productivity has been presented and discussed during June, 2015. The states 1, 2 and 3 directions were east, east-south and south direction respectively, while the water level in all states was 1cm and the other design parameters such as, evacuated tubes number and the tilt angle of the evacuated tube for all states are fixed.

Figure (11) shows the experimental results of water productivity for states 1, 2 and 3 as a function of direction on the 14th of June 2015. This figure shows that the water productivity has been influenced by the direction of the solar still. The daily production for the states 1, 2 and 3 (from 8:00 AM to 17:00 PM) were 4024, 3608 and 3982 ml/m² respectively.

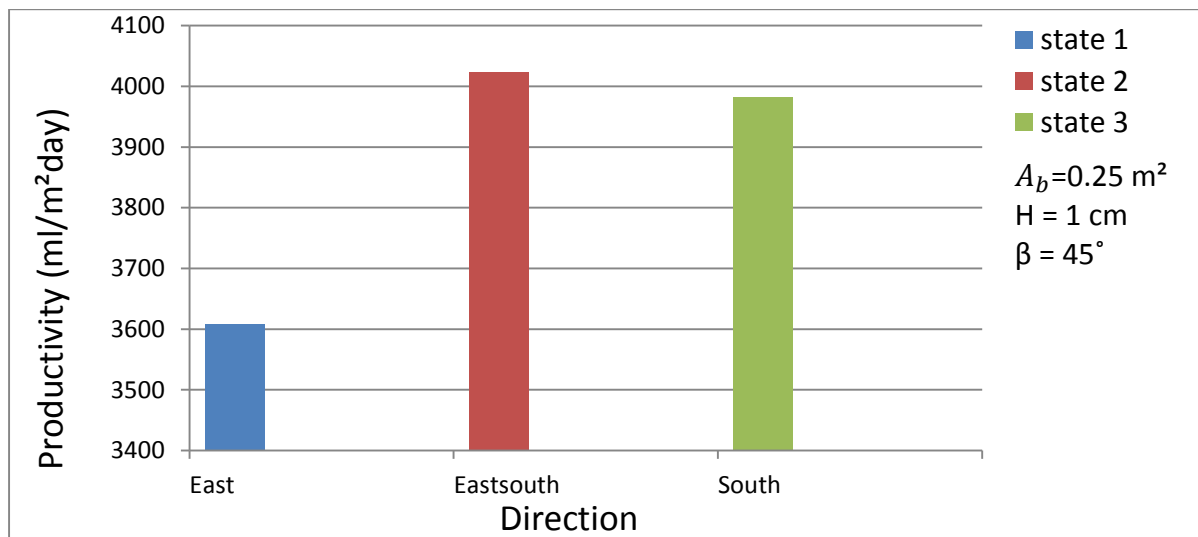


Fig. 11. Water productivity as a function of direction for all states on the 14th of June 2015.

Figure (12) shows the experimental results of water productivity for the states 1, 2 and 3 as a function of time on the 14th of June 2015. The amounts of water productivity, relative to states 1, 2 and 3, have increased gradually from 208, 190 and 160 ml/m² respectively starting from the early hours of the day at 8:00 AM until 12:00 AM to the maximum values of 507, 596 and 590 ml/m² respectively. However, the water productivity amount of state 2 was larger than the other states due to the high absorption of state 2 to the solar intensity during this period. After 12:00 AM, water productivity has decreased due to the decreasing solar intensity that reached state 2 due to the oblique dropping of the sun rays on state 2, where the water productivity of state 3 became more than the other states. But, the daily productivity of state 2 was more than the other states. From the productivities of the three states, it can be seen that the best direction was found to be toward the east-south direction during June in Basrah city.

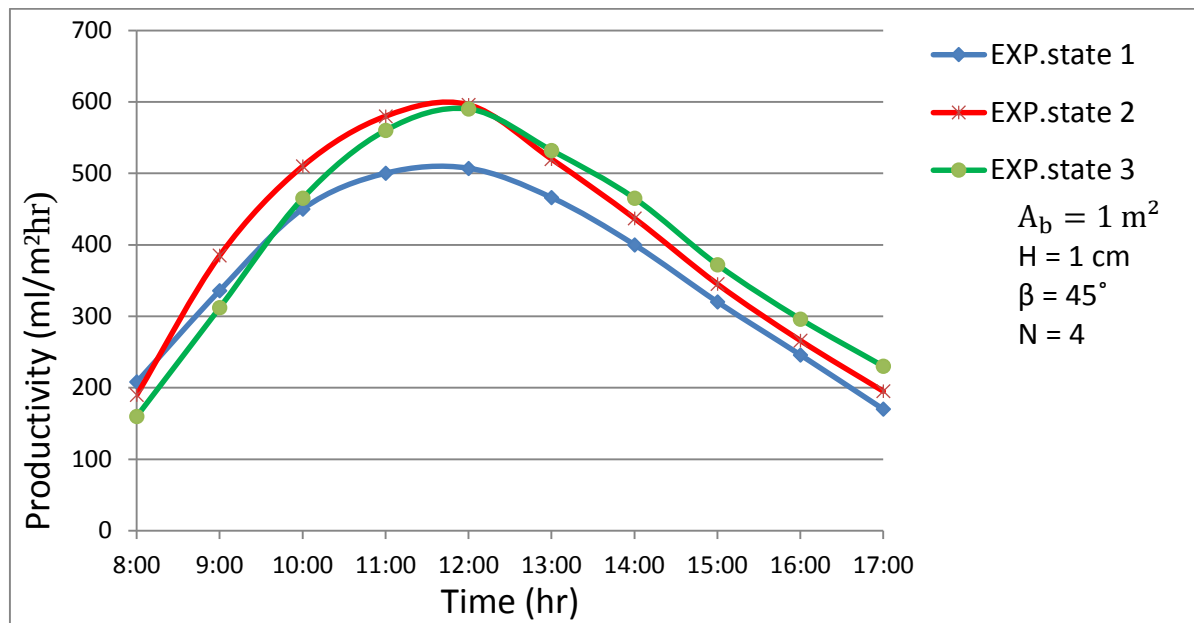


Fig. 12. Water productivity as a function of time on the 14th of June 2015 for all the states

The average thermal efficiency for each of the states on the 14th of June was about 21.27%, 25%, and 24% respectively as shown in figure (13). The percentage enhancement in the daily productivity due to a change in the direction of the solar still from the east to the east-south and from the south to the east-south directions were about 10.33% and 1% respectively.

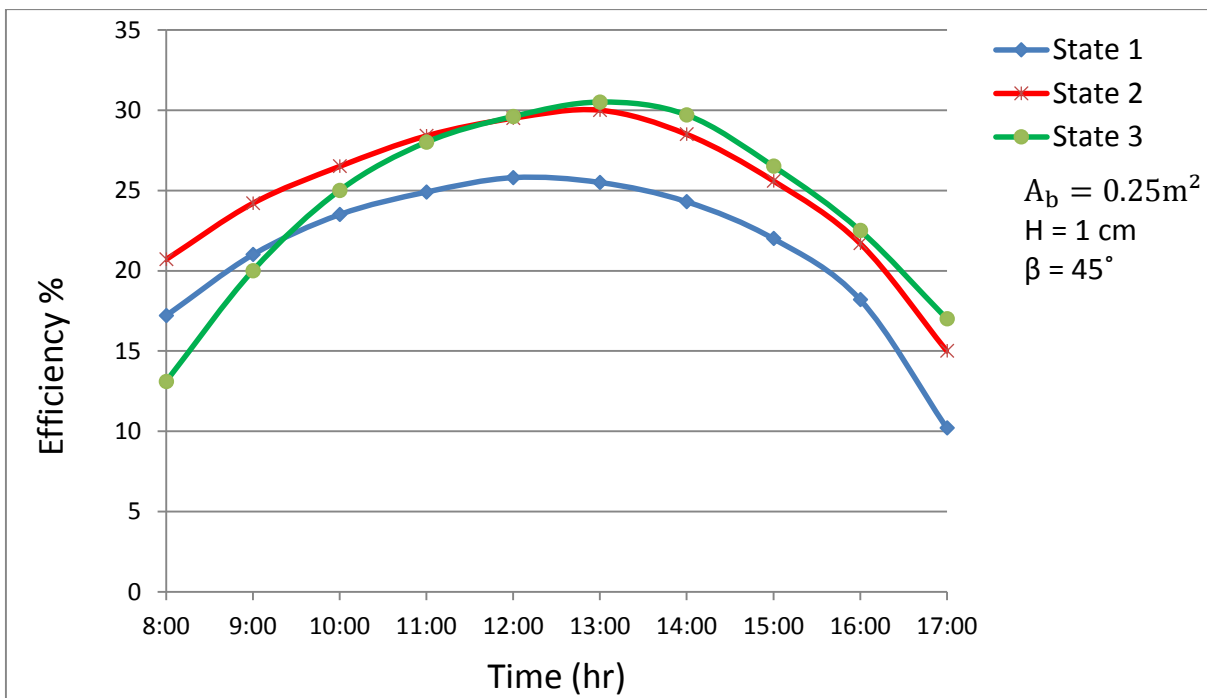


Fig. 13. Efficiency as a function of time on the 14th of June 2015 for all the states.

6- CONCLUSION

A solar still with an evacuated tubes collector was built up and studied under actual climatic conditions of Basrah city. A theoretical project is constructed to predict the performance and

productivity of an active double slope solar still using different operational parameters. Experimental verification on the distillation effectiveness of the solar still have been done. In the

two cases, the relationship between water productivity and solar intensity is directly proportional. From the above, it can be concluded that the amount of distilled water produced depends on the water level in the basin of the still, and on the solar still orientation. Whenever the level of water in the still basin decreases, the water productivity increases. However, the percentage of enhancement in the daily productivity due to a decrease in the water level from 4 cm to 1 cm in the basin equal, was equal to 18%. Also, the best direction of the wind was found to be the east-south direction in Basrah city. The percentages of wind enhancement in daily productivity due to the use of the east-south directions instead of the east and south directions were about 10.33% and 1% respectively.

REFERENCES

- [1] Al-Kharabsheh, S.& Goswami, D.Y. " Theoretical Analysis of a Water Desalination System Using Low Grade Solar Heat", Journal of Solar Energy Engineering, Vol. 126, MAY 2004.
- [2] Alkan, P.I. "Theoretical and Experimental Investigations on Solar Distillation of İYTE Gülbahçe Campus Area Seawater", M.SC Project, İzmir Institute of Technology, 2003.
- [3] Singh,R.V., Kumar, S., Hasan, M.M. , Khan, M. E.& Tiwari, G.N. "Performance of a solar still integrated with evacuated tube collector in natural mode". Desalination, Vol 318, P.25–33, 2013.
- [4] Kim, Y. & Han, G.Y& Seo, T. "An evaluation on thermal performance of CPC solar collector". International Communications in Heat and Mass Transfer, Vol 35, P. 446 – 457, 2008.
- [5] Sadiq, A. Sh. "Artificial Neural Network for Evaluating the Performance of a Solar Still Using a Heating Pipe Evacuated Tubes Collector". M.SC project, University of Basrah, 2013.
- [6] Medugu, D.W. & Ndatuwong, L.G. "Theoretical analysis of water distillation using solar Still". Physical Sciences, Vol.4, p.705, 2009.
- [7] Badran, O. "Theoretical Analysis of Solar Distillation Using Active Solar Still". Int. J. of Thermal & Environmental Engineering, Vol. 3, P.113, 2011.
- [8] Kalogirou, S.A. "Seawater desalination using renewable energy sources". Progress in Energy and Combustion Science, Vol. 31, P.242, 2005.
- [9] Badran, O.O. & Abu-Khader, M.M. "Evaluating thermal performance of a single slope solar still", Heat Mass Transfer, P. 985, 2007.
- [10] Owaid, A.I., Tariq, M., Issa, H., Sabeeh, H. & Ali, M.", The heat losses experimentally in the evacuated tubes solar collector system in Baghdad-Iraq climate". Issue 4, Vol. 2, P. 13-24, Apr 2014.
- [11] Sampathkumar, K., Arjunan, T. V., Pitchandi, P.& Senthilkumar, P. "Active solar distillation-A detailed review". Renewable and sustainable energy reviews, Vol. 14, P. 1503–1526, 2010.
- [12] El-dessouky, H.T. & Ettouney, H.M. "Fundamental Of Salt Water Desalination" Elsevier Science, 1st Edition, 2002.