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Improving the productivity of solar still using evacuated tubes

Qays A. Rashak, Ala'a A. Jassim, Husam N. Khanfoos

Mechanical Engineering Department, College of Engineering, Basrah University, Ministry of Higher Education & Scientific Research, Basrah, Iraq.

Abstract
The nature of life and population growth makes the rate of water consumption to be very high, also the operation costs of the conventional methods of the desalination process are very expensive and unfriendly to the environment; therefor it is very important to find new, cheap, clean and simple methods for producing drinkable water such as solar energy desalination systems. To improve the performance of solar still by using evacuated tubes. The effect of parameter variables such as solar intensity, wind velocity, the tilt angle and numbers of the evacuated tubes are studied and then discussed. It can be concluded that the maximum productivity of water has achieved when the tilt angle of the evacuated tubes was 15˚ on the horizone using four evacuated tubes.

Keywords: Evacuated tube collector; Efficiency; Distillation; Solar still.

1. Introduction

Desalination processes require significant amounts of energy. Due to the high cost of convention energy sources, which are also environmentally harmful, renewable energy sources particularly solar energy have gained more attraction since their use in desalination plants will save conventional energy for other applications, and reduce environmental pollution [1].

Desalination is now successfully practiced in numerous countries in the Middle East, North Africa, southern and western US, and southern Europe to meet the industrial and domestic water requirements [2]. Singh et al. [3] studied a Solar still integrated with parabolic concentrator, evacuated tube collector (ETC) and flat plate collectors (FPC) and that have been tried by various scientists to enhance the daily yield. The flat plat collector is popular due to its low maintenance cost and simple design. However, the FPC has 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 of the sun tracking by its tubular design. However, Kim et al. [4] have found a significant increase in the outlet temperature of water and 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 which used for solar energy exploitation due to its simplicity and low maintenance compared to 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 can only be used for a low-pressure system, as the tubes that can only withstand a few meters of water head. The present study is focused on the thermal modeling and performance evaluation of a solar still integrated with an evacuated tube collector in natural mode. The effect of water depth in the solar still basin on yield, energy and exergy efficiencies has been estimated. System has been optimized to find the best combination between the size of ETC and water depth in the solar still for optimum performance. Sadiq [5] presented a study for evaluating the performance of active double slope solar still using heating pipe evacuated tube theoretically and compared it with the experimental results relative to Basrah city climate. The system consisted of solar still basin with an area of ($1m^2$) connected to eight of evacuated tubes. He also studied the effect of solar intensity, wind velocity and evacuated tubes on the water productivity. His tests have extended for the period of January to August 2013. He concluded that the water productivity has increased with increasing the solar intensity and the wind velocity. The water productivity of the solar still system with evacuated tubes has about 11.23 kg for the period between 800: AM to 17:00 PM while the thermal efficiency of the system for the same period was 16.44% and showed that the values of water productivity have increased by about 43.35% compared with those of the conventional solar system.

2. System description and experimental steps

The experimental work includes three solar still systems which are similar in the structure, shape and dimensions. Each solar still system consists of a double slope solar still used to intervene the maximum amount of solar radiation. The area of basin was $0.25m^2$ (0.5m length, 0.5m width). It is provided in each side with a channel which sloped 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 cover was taken as 30^O to the horizone. 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 diameter 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 come back 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 1 shows the whole system of the work of solar still with all parts and connections.

3. Results and discussion

The experimental work used for verifying the effect of operating and designing parameters such as solar intensity, air velocity, the tilt angle and number of evacuated tubes on the performance of solar still with evacuated tubes collector were investigated.

3.1 Effect of tilt angle of the evacuated tube on water productivity

The effect of the tilt angle of evacuated tube on the water productivity has been presented and discussed during July, 2015.

The tilt angles of evacuated tube for the states 1, 2, and 3 were 15˚, 30˚and 45˚ with the horizon respectively. Also, the other designing parameters 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 2. 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 were variable from time to time through the month, as well as, the appearance of some clouds in the sky during some days which effects on the water productivity. From Figure 2 it can be noticed that the highest productivity was on the 21st of July.

Figure 1. System of the work of solar still.

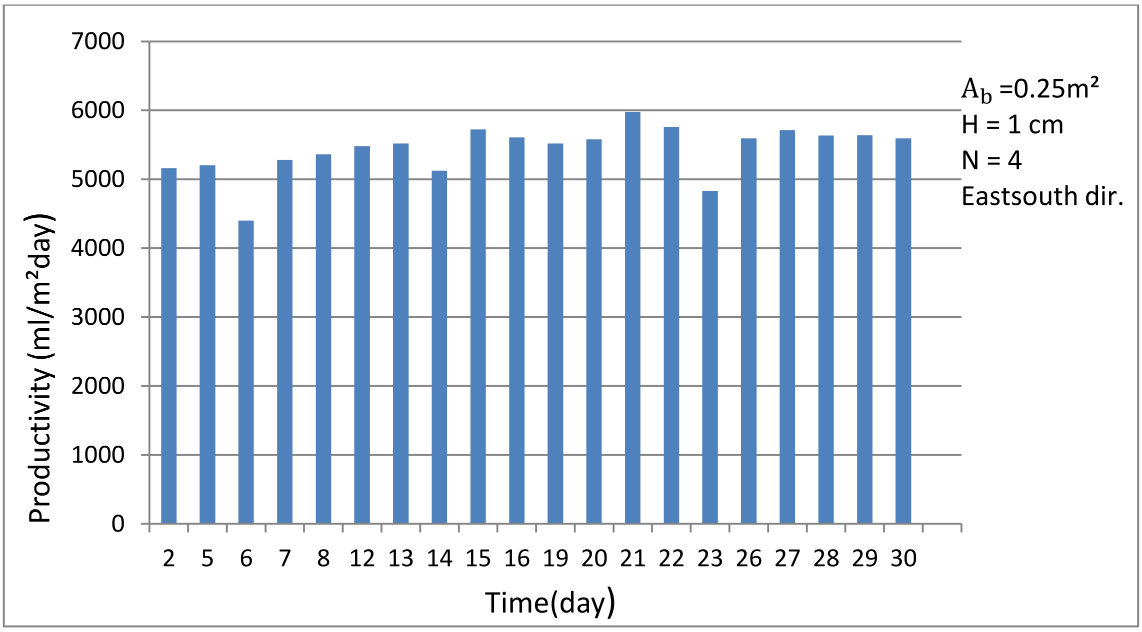

Figure 2. Water productivity per day during the period between 2nd-30th of July 2015 for state1.

Figure 3 shows the experimental results of water productivity for all the states at the period between 8:00 AM to 17:00 PM on the 21st of June 2015. The water productivity was inversely proportional with the tilt angle of evacuated tube during the summer season. Whenever the tilt angle increases, the water productivity decreases. This due to the evacuated tubes absorption of solar radiation has decreased when the tilt angle of evacuated tubes increases because the sun rays are vertical approximately during July month. Therefore, whenever the tilt angle of evacuated tubes was large, the dropped rays on the evacuated tubes were inclined. Where the daily production of the states 1, 2 and 3 were 5978, 5097 and 4312 ml/m^2 day respectively. From Figure 3 it can be noticed that the amount of water productivity from the state 1 was larger than the other states because the difference in temperatures between the water in the basin and the glass cover was higher than the other states. This due to the evacuated tubes having tilt angle equal to 15˚where its absorber for solar radiation is larger than the tilt angles of 30˚ and 45˚.

Therefore, the temperature of the outlet water from evacuated tubes was high in comparison with the other evacuated tubes.

The water productivity increased gradually from 328, 280 and 222 ml/m^2 at 8:00 AM to maximum value of 880, 775 and 660 ml/m^2 at 12:00 AM for the states 1, 2 and 3 respectively. After 12:00 AM it decreased gradually until it reached 344, 308 and 268 ml/m^2 at 17:00 PM for the states 1, 2 and 3 respectively due to the solar radiation increasing gradually from 639 W/m^2 at 8:00 AM to a maximum value of 1205 W/m^2 at 12:00 AM. Therefore, it decreased gradually until it reached 696 W/m^2 at 17:00 PM, where the water productivity increased when the solar radiation increased. From the above it can be concluded that the amount of water productivity depends on the tilt angle of the evacuated tubes of the still, whenever the tilt angle of the evacuated tubes with horizon has decreased, the water productivity increased.

The average thermal efficiencies were about 40.4%, 34.7% and 29.4%, for the states 1, 2 and 3 respectively on the 24thof July 2015 as shown in Figure 4. The percentage of enhancement in daily water productivity due to decrease the tilt angle of the evacuated tubes from 45° to 15° was 27.8%.

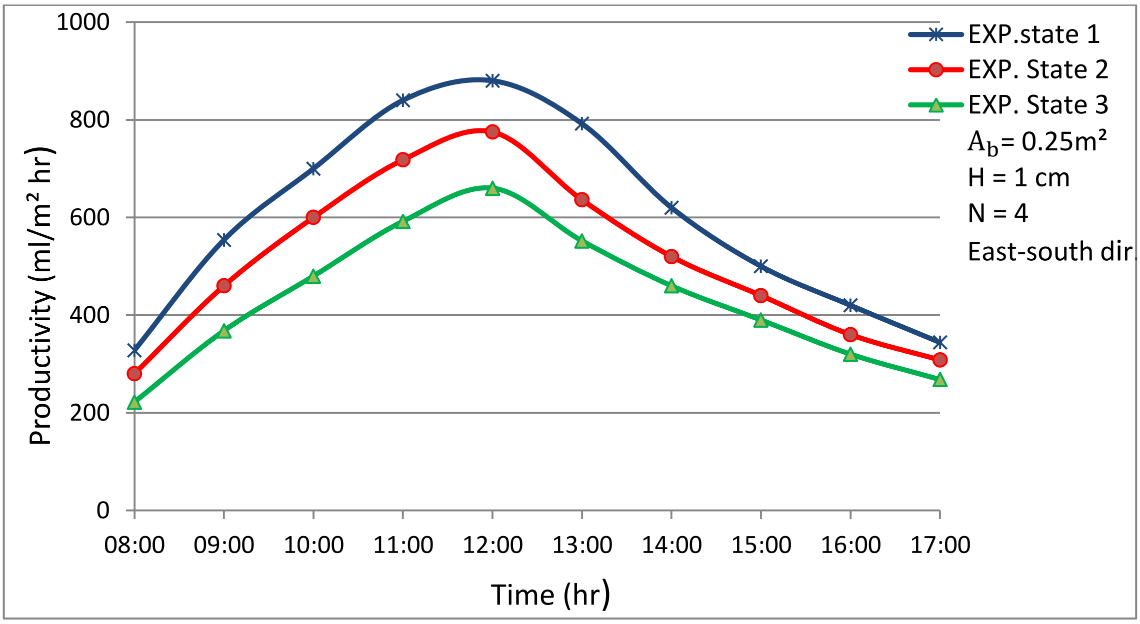

Figure 3. The water productivity as a function of time on the 21st of July 2015 for all the states.

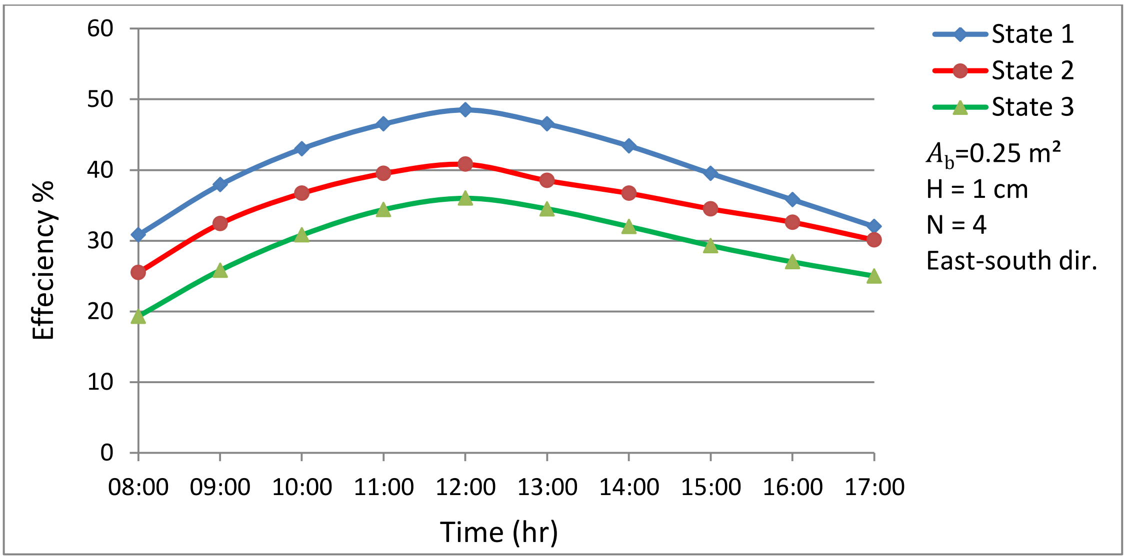

Figure 4. The efficiency of the still as a function of time on the 21st of July 2015 for all the states.

3.2 Effect of operating variables on the water productivity

The effect of operation variables such as solar intensity, wind velocity and temperatures of water, glass cover and the outlet water from collector on the water productivity have been presented and discussed. The recording data have been measured on the 21st of July 2015.

The solar intensity has been measured and recorded as in Figure 5 and its effects on the water productivity of the solar still have been studied and discussed. The values of the solar still productivity have been recorded as shown in Table 1 for the period between 8:00AM and 17:00PM. The results in Table 1 show that the water productivity for all states increase gradually at the period between 8:00 AM to 12:00 AM where it reached the maximum value at 12:00 AM because of the increasing solar intensity from 639 W/m^{2}hr to maximum value of about 1205 W/m^{2}hr during the period between 8:00 AM to 12:00 AM which have contributed to increase the amount of water vaporized inside the basin of the still. Then the water productivity decreased with the time during the period after 12:00 AM because of decreasing solar intensity.

Figure 6 and Table 1 shows that the air velocity increased gradually from 0.9 m/s at 8:00AM to its maximum value of 1.5 m/s at 12:00AM then, after this period it began decreasing until it reached 0.8 m/s at 17:00PM. The air velocity has contributed to increase the water productivity. Whenever the air velocity increased, the air and glass temperatures reduced and this lead to increase the amount of condensing water vapor.

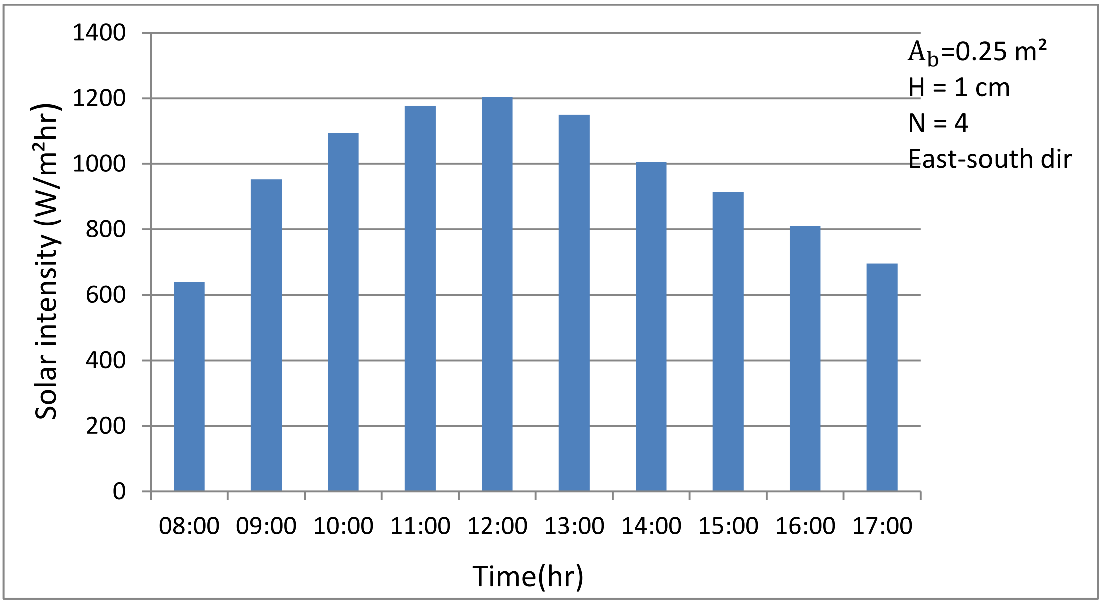

Figure5. The solar intensity as a function of time on the 21st of July 2015.

Table 1. The solar intensity, wind velocity and water productivity for all states as a function of time on the 21th of July 2015.

Time (hr)	Solar intensity (W/m^{2}hr)	Wind velocity (m/s)	Temperature of the model 1 (˚C)			Temperature of the model 2 (˚C)			Temperature of the model 3 (˚C)			Productivity of model 1 (ml/m^{2}hr)	Productivity of model 2 (ml/m^{2}hr)	Productivity of model 3 (ml/m^{2}hr)
			T_w	T_g	T_{out}	T_w	T_g	T_{out}	T_w	T_g	T_{out}			
08:00	639	0.9	48.7	41	99	46.4	40	97	44.2	40	95	328	280	222
09:00	953	1	58.5	47.4	100	56.2	46	100	54.4	46	99	554	460	368
10:00	1094	1.1	64	52.3	101	62.5	52	101	61.2	52	100	700	600	480
11:00	1177	1.3	66.5	54.2	101	64.5	53.2	101	63.4	53.2	101	840	718	592
12:00	1205	1.5	70	58.7	101	67.8	57.4	101	66.9	57.4	101	880	775	660
13:00	1150	1.3	68.3	57.2	101	66.4	56.5	101	65.4	56.2	101	792	636	552
14:00	1006	1.1	66	56	99	64.1	55	98	63.2	55	97	620	520	460
15:00	915	1.05	64.2	55.2	95	62.1	53.4	90	61	53.3	89	500	440	390
16:00	810	0.95	62	54	90	60.2	52.2	85	59	52	83	420	360	320
17:00	696	0.8	59.7	52.7	81	58.1	51	79	57.2	51	77	344	308	268

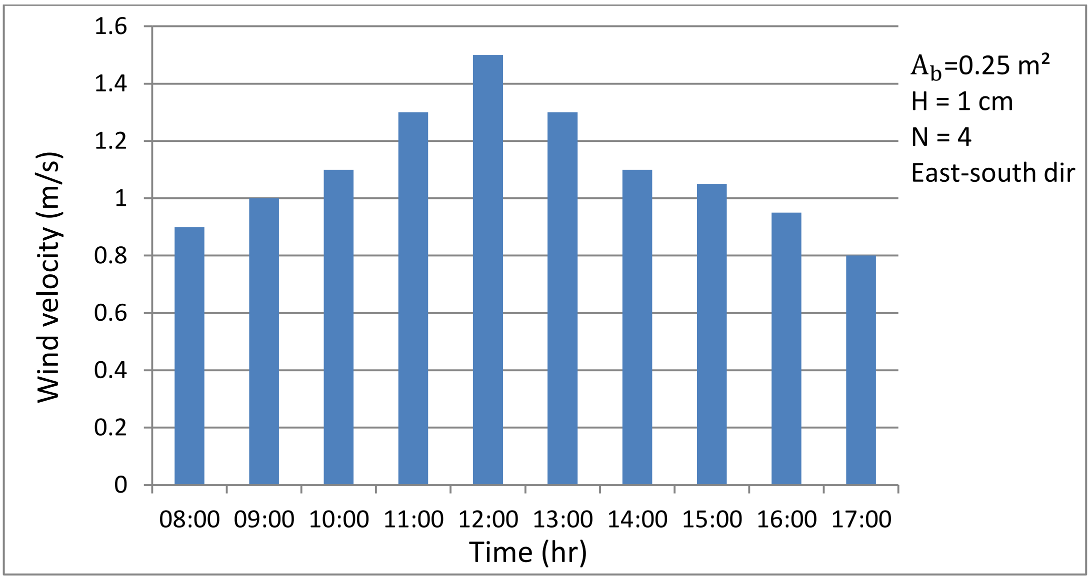

Figure 6. The wind velocity as a function of time on the 21st of July 2015.

3.3 Effect of the evacuated tubes number on the water productivity (fourth case)

In the fourth case (4C) the effect of the evacuated tubes number on the water productivity has been presented and discussed during August 2015. Where the states 1, 2 and 3 have used 4, 2 and 0 evacuated tubes respectively. Also the other designing parameters for all states are considered as constants (the water level in the basins was 1 cm, the direction was east and tilt angle of evacuated tubes was 15° for all the states). Where the water productivity of the state 1 during August 2015 has been recorded as shown in Figure 7.

Figure 7 shows that the water productivity from the state 1 during the August which has fluctuated due to the variation of the intensity of solar radiation, wind speed, ambient temperature and the wind direction during the month, as well as the appearance of some clouds in the sky in some days of the month and all those effects on the productivity. From Figure 7 it can be noticed that the highest productivity was on the 16th of August, therefore the fourth case was studied and discussed on the 16th of August 2015.

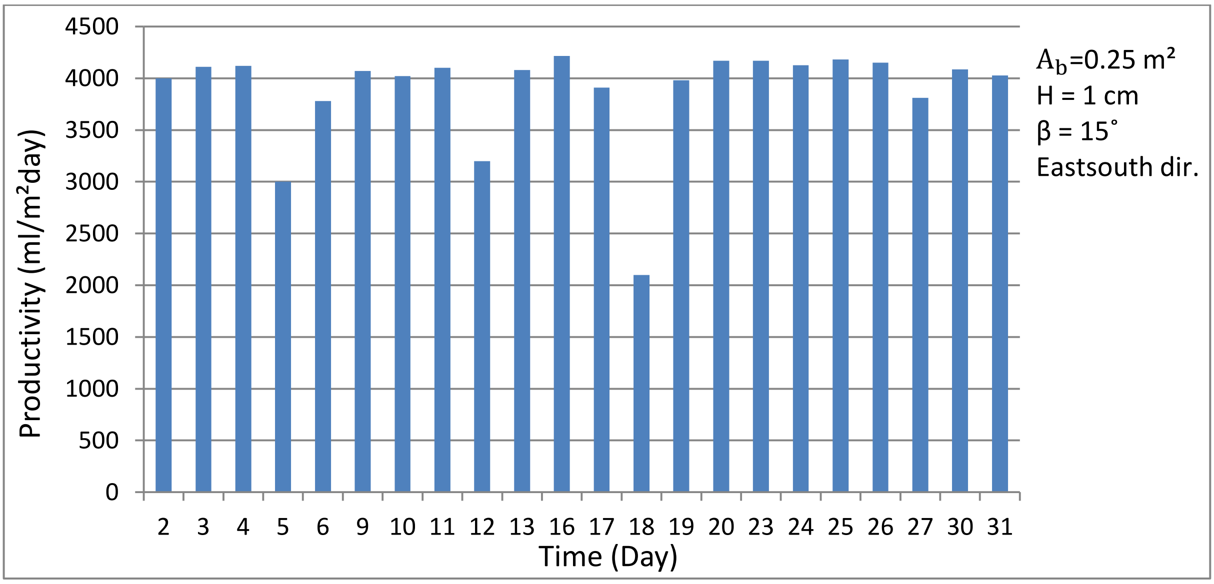

Figure 7. Water productivity per day during the period between 2-31 of August 2015.

Figure 8 shows the experimental results of water productivity for the states 1, 2 and 3 during the period between 8:00 AM to 17:00 PM on the 16th of August 2015. The water productivity was proportional with the number of evacuated tubes. Whenever the number of evacuated tubes increase, the productivity of the water increases too. Because of increasing the heating of the outlet water temperature from the collector, where the daily production of the states 1, 2 and 3 were 4216, 3060 and 2500 ml/m^2 day respectively. From Figure 8 it can be noticed that the amount of water productivity from the state 1 was larger than the other states because the difference in temperatures between the water in the basin and glass cover was higher than the other states due to the evacuated tubes.

The water productivity increases gradually from 268, 160 and 60 ml/m^2 at 8:00 AM to maximum values of 620, 484 and 460 ml/m^2 at 12:00 AM then after 12:00 AM it decreased gradually until it reached 160, 80 and 48 ml/m^2 at 17:00 PM for the states 1, 2 and 3 respectively. The solar radiation increased gradually from 609 W/m^2 at 8:00 AM to maximum value of 1181 W/m^2 at 12:00 AM, then after it decreased gradually until it reached 656 W/m^2 at 17:00 PM, where the productivity increased when the solar radiation increased. Therfore, it can be concluded that the water productivity depends on the number of evacuated tubes of the solar still, whenever the number of the evacuated tubes has increased, the water productivity would have increased too.

The average thermal efficiency for the states 1, 2 and3 on the 16th of August were about 23.6%, 17.2% and 20.3% respectively as shown in Figure 9. The percentage of enhancement in daily water productivity due to use four evacuated tubes about 40.7%, while the percentage of enhancement in daily productivity due to increase the number of evacuated tubes from two to four tubes about 27.4%.

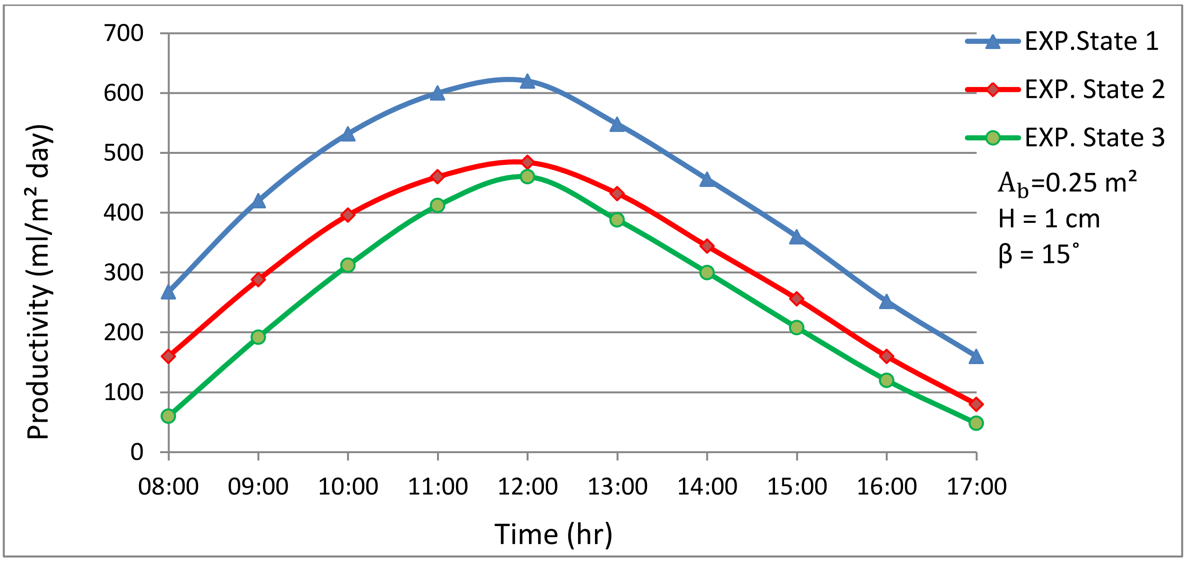

Figure 8. The water productivity as a function of time on the 16th of August 2015 for all the states.

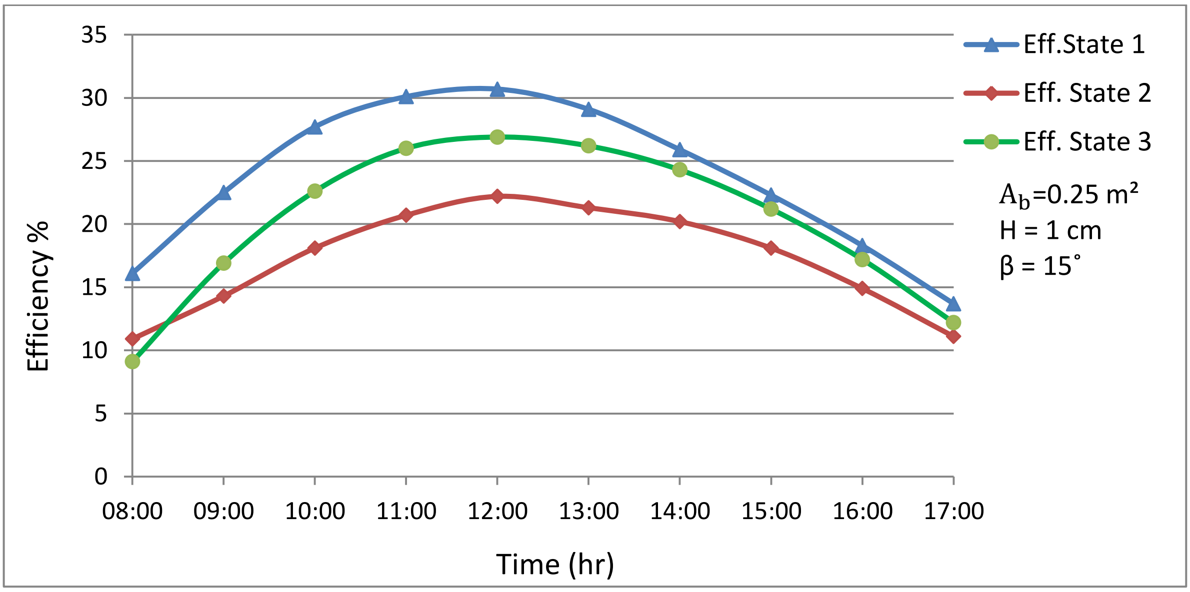

Figure 9. The efficiency of the still as a function of time on the 16th of August 2015 for all the state.

4. Conclusion

A solar still with evacuated tubes collector was constructed and studied under actual environmental conditions of Basrah city. A theoretical work is constructed to predict the performance and productivity of active double slope solar still using different operational parameters. Experimental investigations on the distillation performance of the solar still have been carried out. In the two cases, the relation between water productivity and solar intensity is direct to proportional. The maximum productivity of water has achieved when the tilt angle of the evacuated tubes was 15˚ on the horizone, where the percentage of enhancement in daily water productivity was 27.8% in comparison with other angles and the average thermal efficiency was about 40.4%. The productivity of distilled water increase when the number of evacuated tubes have been increased, where the percentage of enhancement in the daily water productivity due to use four evacuated tubes was about 40.7% and the average thermal efficiency was about 23.6%.

Nomenclature

A_b	Area of the basin still	H	Water depth in the basin (cm)
β	Tilt angle of evacuated tube(dgree)	N	Number of evacuated tubes

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Qays A. Rashak, Ph.D. in Mechanical Engineering, College of Engineering, Basrah University ‹Iraq. Specialization: Fluid Mechanics, Graduation Date: 2003. M.Sc. In Mechanical Engineering ‹College of Engineering/University of Basrah/Iraq. Specialization: power & Desalination plant, Graduation Date 1993. B.Sc. In Mechanical Engineering/ College of Engineering/University of Basrah, Iraq . Specialization: General Mechanics, Graduation Date: 1990.
E-mail address: alsafi.husam@yahoo.com

Ala'a Abdulrazaq Jassim, Ph.D. in Chemical Engineering, College of Engineering, Basrah University ‹ Iraq. Specialization: water desalination and Unit operations, Graduation Date: 2003. M.Sc. In Chemical Engineering, College of Engineering/ University of Basrah/ Iraq. Specialization: Unit operations, Graduation Date 1996 B.Sc. In Chemical Engineering/ College of Engineering/University of Basrah, Iraq. Specialization: chemical engineering, Graduation Date: 1992.
E-mail address: alaahade88@yahoo.com

Husam N. Khanfoos, Researcher in Thermal Engineering, Department of Mechanical Engineering, Basrah University, Iraq. B.Sc. In Mechanical Engineering, College of Engineering, University of Basrah, Iraq. Specialization: General Mechanics, Graduation Date 2003.
E-mail address: alsafi.husam@yahoo.com

