"Experimental and Theoretical Study of a Multi- Stage Solar Still Connected to Evacuated Solar Collector Tubes"

Muntadher. H. Abed **Muna S-Kassim** **Fouad A. Saleh**

Department of Mechanical Engineering, AL-Mustansiriyah University, Baghdad, Iraq

engmuntadher.alsafi1987@gmail.com munasaljabri@gmail.com foads2003@yahoo.com

Submission date:- 18/11/2018	Acceptance date:- 16/12/2018	Publication date:- 19/12/2018

Abstract:

Solar distillation is an effective and a useful method to solve the problem of water scarcity usable on the surface of the earth. A multi-stage solar still was used, and the performance of it was improved by linking it to (Evacuated Solar Collector Tubes), the rate of increase in productivity is about (38%). Practical and theoretical calculations were carried out on two cases. The first case was the basin of the first stage containing water only; the second case was the basin containing the fiber of the palm. When comparing the two cases there was a similarity between the two cases, but the addition of leaf fiber improved the increase in night productivity. The rate of increase in night productivity is about (25%).This type of solar still was a modern technology in improving the performance of multi-stage solar still.

Keyword: Multi-stage, Solar still, Potable water, Solar distillation, Fiber palm.

Symbol List:

symbol	The meaning of the symbol	Measuring unit
Qeff	Rate of thermal energy affecting	(watt)
mevi*	Vaporized water mass rate	(kg/second)
hfgi*	Latent heat of evaporation (corrected)	(j/kg)
hfgi	Latent heat of evaporation	(j/kg)
cpi	Thermal capacity of water at each stage	(J/kg. K)
cpw	Thermal capacity of salty water	(J/kg. K)
MWi	Mass of salty water at each stage	(kg)
Tsti	Water surface temperature at each stage	(c°)
Tcoi	The temperature of the condensate at each stage	(c°)
dTsti / dt	Rate of time change of water surface temperature	(c°/ second)
$Qlosses_i$	The amount of heat lost at each stage	(watt)
Mpoti	The amount of potable water produced from each stage	(kg)
psti	Molecular pressure of the water surface at each stage	(N/m^2)
Pcoi	Molecular pressure of the condenser surface at each stage	(N/m^2)
hstcoi	convection heat transfer coefficient between the water surface and the lower part of the next stage	$(W/ m^2. K)$
hmevi	Evaporation mass transfer coefficient at each stage	$(W/ m^2. K)$
Asi	Surface area of the water	(m^2)
Ttcin	The temperature of the water entering the evaporator	(c°)
Ttcout	Water temperature outside the evaporator	(c°)

List of Acronyms

Acronym	Description
MPOT exi	The amount of experimental potable water at stage
MPOT thi	The amount of theoretical potable water at stage
Tst_i	The temperature of the water surface at stage
MPOT ex ri	The amount of experimental potable water at stage for previous research
M_iC_I	Amount of potable water at case
M $night_i$	Amount of night productivity at case
T_i $case_i$	The temperature of the water surface at that stage of the specific case

1. Introduction:

One of the real problems facing the world is the scarcity of potable water. Most of the water available from natural sources such as the seas and lakes is saline water that is not suitable for drinking. Today the world has turned to saltwater for desalination use in places where fresh water is lack. On the other hand, most desalination plants use fossil energy sources such as gas, it is an energy source that is harmful to the environment and these types of energy are the causes of global warming on the surface of the earth. Scientists have introduced renewable energies to solve many of the life problems and the most important kind of renewable energy is solar energy. This energy has entered into the field of desalination. Solar desalination is a direct application of solar energy to desalination. Desalination defined as heat salt water to boiling point and form water vapor that is then condensed into potable water. Solar desalination classified to:

A. Indirect solar desalination

B. Direct solar desalination

Solar desalination uses simple device called solar still. The work principle of solar still is similar to the principle of rain formation. There are many types of solar stills but in this study the focus will be on the study of multi-stage solar stills.[1]

Some previous research will be presented regarding this type of still: Maha Rahman Rahi (2016) Worked a practical and theoretical study of the design of a Multi-stage solar still drew its energy from (parabolic trough collector), study was conducted in the city of Kirkuk and Found that the highest productivity and performance of solar energy was during month of (August) and the increase in productivity (10-20 %) from the solar still single-basin. [2]

Obaid younas, Fawzi Banat, and Didarul islam (2014) In this research used a multi-stage solar still was coupled with a point-focus Fresnel lens in the process of solar distillation tests were conducted in field condition at the Petroleum Institute, Abu Dhabi. Deviation was (5%) in daily yield of a multi-stage solar still. The highest productivity was (10 Kg/m2 .day) in May and June; the least productive was (4.8Kg/m2day) at the month December. [3]

Patel et al.(2014) conducted study of previous research on the performance of solar still and the factors affecting the increased distillation of salty water, the study showed that increasing the difference in temperature between the transparent cover and the temperature of the water surface increases the mass of water vapor, leading to an increase in production, also productivity increases when distance between evaporator and condenser was low and there was absorbent material at the base, studies have shown that multi-stage solar still are more productive than single-stage solar still.[4]

Gawande et al. (2013) manufactured a new type of Multi-stage solar still for the purpose of studying the water depth on its productivity, three different depths of water were taken into the still basin (5mm,7.5mm.10mm), the distillate productivity decreases when the water depth is increased, the distillation productivity was shown at a depth of (5 mm) was higher than depth (7.5mm) by (14.15%) as well as depth of production (7.5mm) higher than the depth of (10 mm) by (22.26%) at the same operating conditions.[5]

Kumar et al.(2012) conducted a theoretical and practical study to found the best design and enhancement the performance of multi-stage solar still (vacuum pressure) and connected to two flat type solar pickup, the solar still was connected to the solar pickups in the two ways first respectively and the second in parallel, the results showed that the optimal design of the solar still was four stages and the distance between one stage and another was (100 mm) and feed rate during the day (55 kg /m2.day), the highest productivity was obtained in March (28kg/m2/day) with still efficiency (50.9%),it was found that the lowest efficiency and productivity of the solar still in December is (24%) (13.3kg/m2/day) respectively, it was also found that the connection of the two solar pickup in parallel produces higher than their respective coupling.[6]. The current study involves the design of a new type of multi-stage solar still, in which the multi-stage solar still was connected to the evacuated solar collector tubes The effect of adding fiber palm in the first stage basin on the performance of solar still will also be studied.

2. Principle of multistage solar still with evacuated solar collector tubes Work:

This type of solar distillate was considered an indirect type because the energy that was used in the process of evaporation was mainly taken from the heat energy of the evacuated solar collector tubes; where the water was heated inside these tubes and then pumped into the heat exchanger fixed inside the basin of the first layer; the process of evaporation and condensation within the solar still passes through four stages.

3. Description of distillation system

3.1. Evacuated Solar Collector Tubes:

Type used in this study consisted of two-layer vacuum tubes made of glass, (12) tubes were used the length of each tube was (180 cm), inner diameter (4.5cm) and outer diameter (6cm); inner part of the tube was painted in black, the high vacuum of the clearance between outer and inner tube to reduce heat loss which caused by convection and conduction to a lowest level. These tubes were connected to the underside of a cylindrical insulated tank, the capacity of the tank (100 liters) filled with water, this water was heated by the tubes and pumped into the evaporator which in turn warms the water inside the basin of the first stage and then returned in a closed cycle to the isolated tank.

3.2. Multi-stage solar still:

In this study, a four basin were manufactured from galvanized alloy, the dimensions of the basins were equal to (120 cm) long and (40 cm) wide. The height of the first basin was (16 cm) and the others basins were (12 cm). Copper vaporizers were installed inside the first basin. The roof of each of the four basins should be covered by the condenser; the condenser was made in the form of a letter (V). The angle of inclination was (165o). Install the water collector inside each basin and at a height of (10 cm) the bottom of the basin for the purpose of collecting drinking water.

3.3 Hot water pump:

In this study, a hot water pump was used with six flow rates and flow was installed at the lowest possible level (3.25 Liter/minute), the pump was calibrated to maintain flow rate. The role of the pump as in keeping the cycle closed.

3.4 Feeding tank:

The tank was manufactured in the form of a cube with a side length of (45cm), The tank was manufactured from a galvanized alloy, the tank was connected to a network of pipes diameter (4mm) that feed water to the four basins, the pipes were connected with water rafts to maintain the water level constant inside the basins.

Figure (1) distillation system

4 Measuring devices:

In this study, multiple types of measuring devices were used. (10) thermocouples of type(K) used to measure the temperature, These thermocouples were used to measure the Water surface temperature and condensation of each stage of the distillate and measure the temperature of the water entering and leaving the evaporator. also a (Solar meter) was used to measure the intensity of solar radiation. To measure the ambient air a thermometer used, finally the amount of water produced was measured using the cylinders listed.

5 Experimental work:

Experimental tests were conducted under the weather conditions of (Baghdad) capital of (IRAQ) located at longitude (44.42°), latitude (33.418°).

5.1. Experimental steps:

There are three steps in the work, the first step included the design, manufactured and transferred of the system to the experimental work place. The second step included the installation of the solar evacuated collector tubes, linking them to the tank and filled the isolated tank by water and connected the tank with the solar still by a pipeline system. On the other hand, this step was included installation of the solar still and calibrated with the ground to maintain a constant level of water inside the four basins. On the other hand included the filling of feeding tank by water and its connection by a pipe network with the solar still. The last step was on the day of experimental work and included the step of operation of the system and take readings, the working day continued from (5:30 am) to (10:00 pm), the readings were taken every half hour.

5.2 Cases taken:

5.2.1. First case:

This case was the main case on which the present study was based, where the productivity of this case was compared with previous research and the other case was compared with it, the first stage basin shall be filled with water for a specified height.

5.2.2. Second case:

In this study fiber palm was added, which was characterized by high absorption of water and available in abundance in nature, On the other hand, study the effect of adding this substance to improve the productivity of solar still, and improve the performance of still in general, a mat of palm leaf was manufactured with a height(1-2cm) .The mat was fixed inside the first stage basin as shown in figure (2).

Figure (2) Fiber of palm in the first basin

6. Theoretical work

6.1. Boundary conditions: There are two types of conditions:

6.1.1. Climate conditions:

Table (1) Climate conditions

Nu of case	Nature of climate	Air Humidity	Wind Speed (Km/hr)	Ta Max (C°)	Ta Min (C°)	Is Max (KW/M^2)
Case1 27/7/2018	Sunny	(11-29)%	(16-36)	44.6	30.6	1117
Case 2 29/7/2018	Sunny	(14-30)%	(15-32)	44.5	29	1134

6.1.2. Operating Conditions:

Table (2) Operating conditions

Nu of stage	Height of water (cm)	Length of basin(cm)	Width of basin(cm)	Mass of water (kg)
Stage 1	4	120	40	18
Stage 2	2.5	120	40	13
Stage 3	2.5	120	40	13
Stage 4	2.5	120	40	13

7. Mathematical Model:

Lumped parameter model was designed to describe the operation of the system; regulated equations were formulated for each stage of the solar still based on mass conservation equations and energy conservation equations, fig (5.1) showed calculations scheme of still with energy balance diagram.

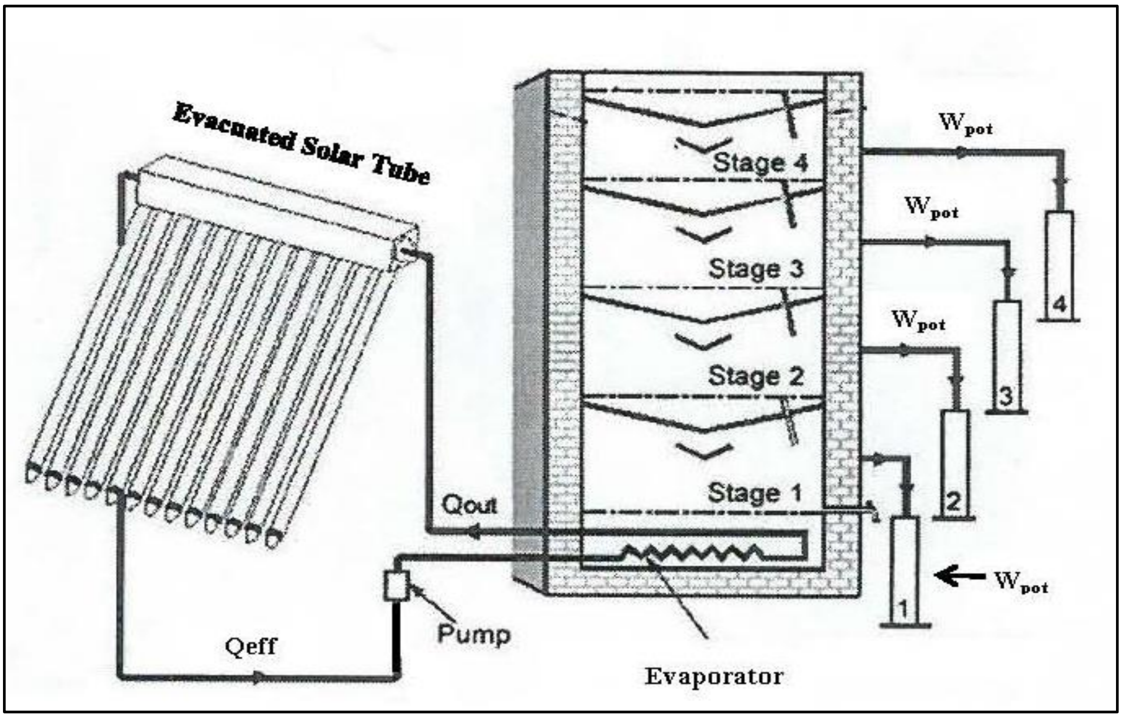

Figure (3) Schematic of solar desalination system

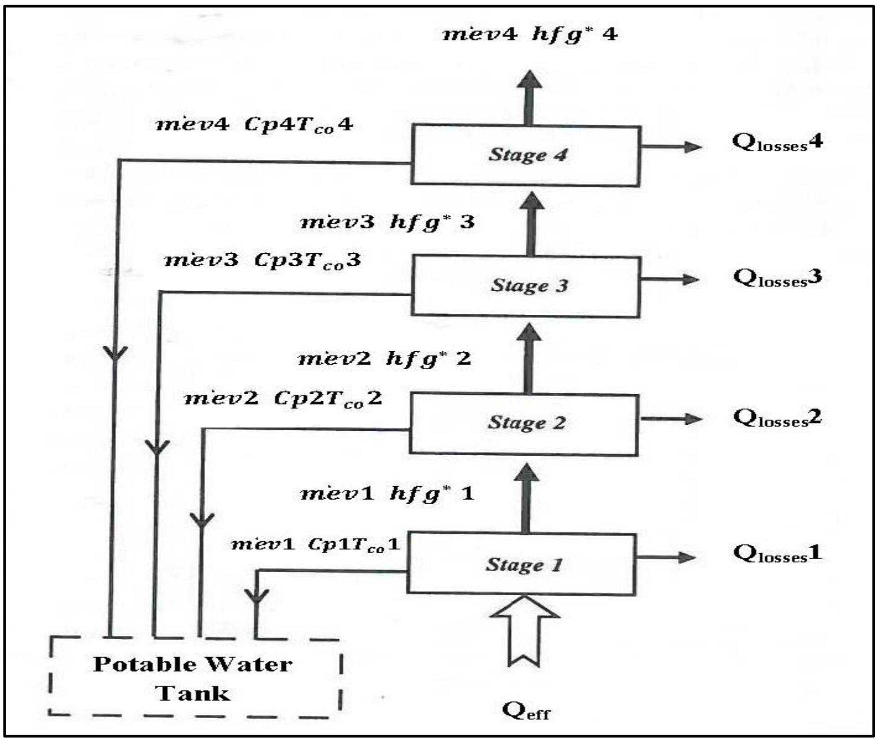

Figure (4) Energy balance diagram

- **Hypotheses governing the mathematical model:**

1. Neglecting the effect of non-intensive gases resulting from thermal heating of the fluid.
2. Amount of evaporated water was equal to the amount of water condensing for each stage of solar still.
3. The product water temperature was equal to the condenser temperature.
4. The volume of water within the four basins was equal in two cases.
5. Surface area of water was equal in two practical cases.
6. Matching physical properties of pure and non-pure water.

The equations below are employed to calculate the productivity of each stage of the solar still.[7]

$$Q_{eff} - m_{ev1} * (hfg1^* + cp*T_{co1}) = M_{W1} * cp * dT_{st1} / dt + Q_{losses\,1} \quad (1)$$

$$m_{ev1} * hfg1^* - m_{ev2} (hfg2^* + cp*T_{co2}) = M_{W2} * cp * dT_{st2} / dt + Q_{losses2} \quad (2)$$

$$m_{ev2} * hfg2^* - m_{ev3} (hfg3^* + cp*T_{co3}) = M_{W3} * cp * dT_{st3} / dt + Q_{losses3} \quad (3)$$

Q_{eff} : It was the energy received by a solar still, it was main source of evaporation within a solar still it can be calculated by equation.[7]

$$Q_{eff} = m_{evtotal} * cp_w * (Ttcin - Ttcout) \quad (4)$$

Mass conversation equation for each stage can be written.[7]

$$dM_{poti} / dt = m_{evi} \quad (5)$$

- **Temperature of condenser surface for each stage**. [2]

T_{sti}: Water surface temperature for each stage

$$T_{co1}= T_{st2}-2 \quad (6)$$

$$T_{co2}=T_{st3}-2.7 \quad (7)$$

$$T_{co3}= T_{st4}-1.11 \quad (8)$$

Dependence of the magnitude of the latent heat. [7]

$$hfg_i= 1000*(3161.5-(2.40741*T_{sti})) \quad (9)$$

The latent heat of evaporation is corrected depending on evaporation and condensation temperatures, as well as depending on the thermal capacity of water according to the following equation. [8].

$$hfg_i^* =hfg_i + (0.68*cp_i*(T_{sti} - T_{coi})) \quad (10)$$

- **Heat capacity of water (cp_i):**

One of the thermal properties of the water represents ability of water to store heat and is known as the amount of heat required to raise the temperature of water one temperature, calculated from equation.

$$Cpi = 1000*[4.2101 - (0.0022*T_{sti})+ (5*10^{-5} *T_{sti}^2)- (3*10^{-7} *T_{sti}^3)] \quad (11)$$

- **Heat transfer coefficient:**

Rate of heat transfer coefficient from the water surface in basin to bottom surface of next stage upward can be calculated according to this equation.[8]

$$h_{stcoi}= 0.884*[(T_{sti} - T_{coi})+(T_{sti}*(p_{sti} - p_{coi}))/(268.9*1000 - p_{sti})]^{(1/3)} \quad (12)$$

- **Water vapor pressure:**

Evaporation and condensation pressure can be calculated by the two equations.[9]

$$p_{sti}=e^{(25.317-5144/Tsti)} \quad (13)$$

$$P_{coi}=e^{(25.317 - 5144/Tcoi)} \quad (14)$$

- **Mass transfer coefficient:**

Function of heat transfer coefficient (hstcoi) calculated from equation.[10]

$$h_{mev}= 16.273*0.001*h_{stcoi}*((p_{sti} - p_{coi})) / ((T_{sti} - T_{coi})) \quad (15)$$

8. Results and discussion:

Two types of results were studied (experimental and theoretical), the experimental results were based on readings taken every half hour. The theoretical results were based on the mathematical equations; these equations were programmed using (MATLAB) to facilitate results.

8.1 First case:

The productivity, evaporation and temperatures will be reviewed from the experimental and practical point of view of this case, which will be compared with the previous research and second case. The practical and theoretical calculations of the fourth stage productivity were neglected because of their very small values

- **Experimental Productivity**

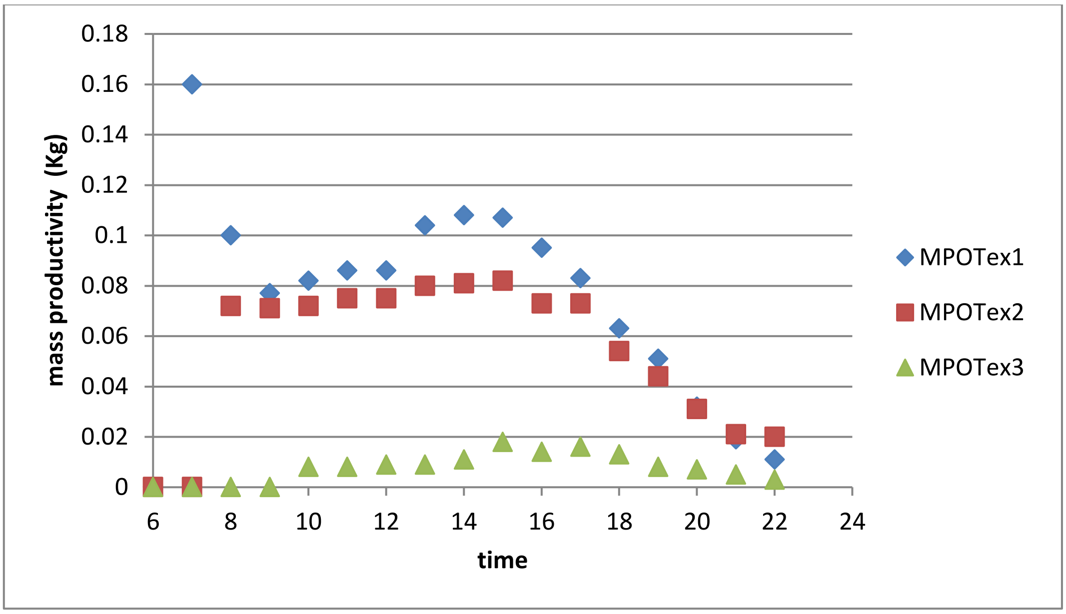

Figure (5) Experimental productivity

In the first stage the highest productivity was at (7:00 am) (0.160 Kg) due to heating water in the isolated tank before the day of experimental work, this water was considered the main thermal source of the evaporation process within the solar still. Then the productivity began to decrease because of the lack of temperature of water supplied from the isolated tank and the reason was due to the closed cycle and the process of circulation occurring inside the tank. After (9:00am), productivity started to increase because of the increase in the amount of solar energy and the reason was due to the increase of the intensity of solar radiation to reach productivity as high as possible at (2:00pm) (0.108 Kg). Once again, the productivity of the first stage decreased after (6:00 pm) due to the receding solar energy and dependence on the hot water temperature already present in the isolated tank. In the second stage productivity started at (8:00 am) (0.072Kg) and started to increase to reach the highest productivity at (3:00 pm)(0.082). After (6:00pm) it began to decline, the productivity of the second stage was less than the productivity of the first stage, but it was noticed after (10:00 pm) that the productivity of the second stage was higher due to the thermal stability achieved in the first stage compared to the second stage. The productivity of the third stage started at (10;00 am) and started increasing to reach the highest productivity at (3:00 pm) (0.018Kg) and then started to decrease after (6:00 pm). The productivity of this stage was less than the previous two stages

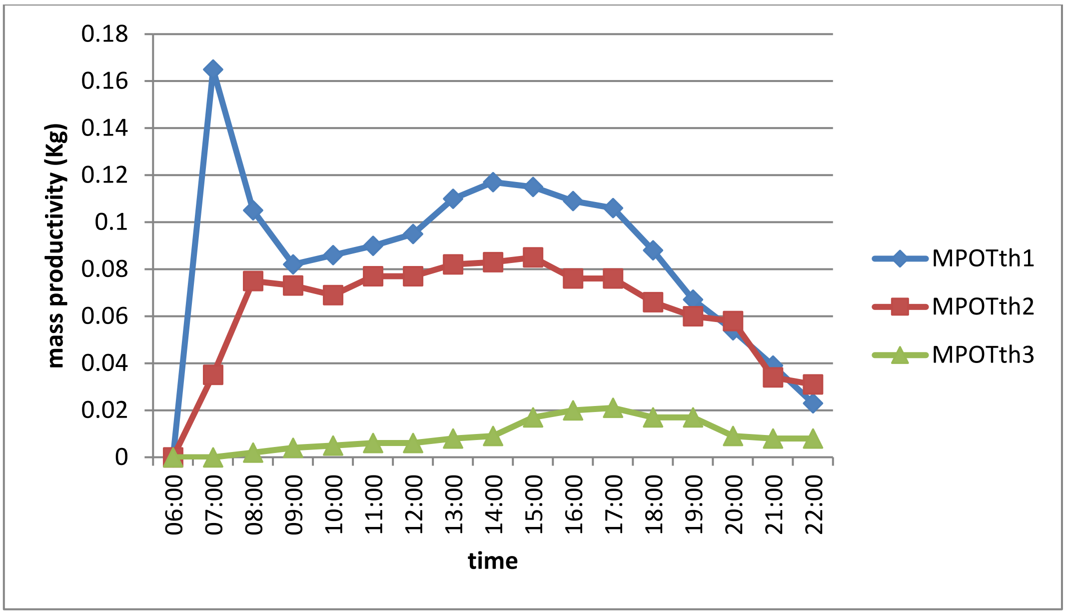

Fig (6) Theoretical productivity

Through the study of theoretical results, there was a convergence of theoretical and practical productivity. On the other hand there was match in the temporal behavior between the two productive. The percentage of validation was (15%).

- **Water surface temperatures:** By studying Figure (7)

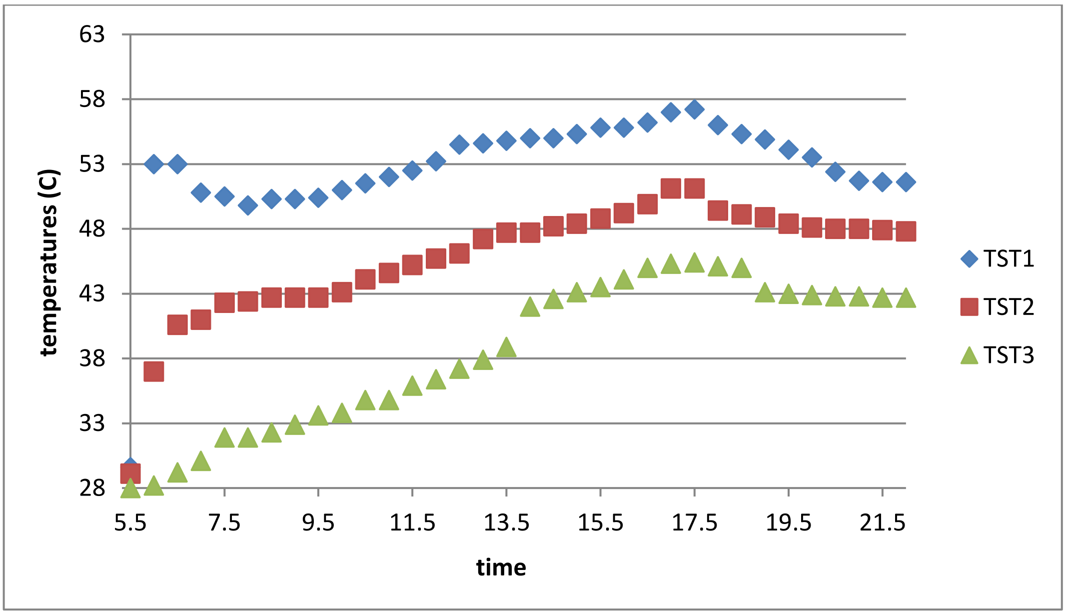

Figure (7) Water surface temperature

By studying the Figure (7) the productivity of the stages increased when the Water surface temperature increased, this was due to the increasing temperature of the surface of the water, causing separation of water molecules near the surface thus, evaporation is increased.

8.2. Compared to the productivity of the first case and the productivity of previous research:

- **Experimental productivity :**

A comparison made with researcher Maha (2016) [2], shown in figure (8)

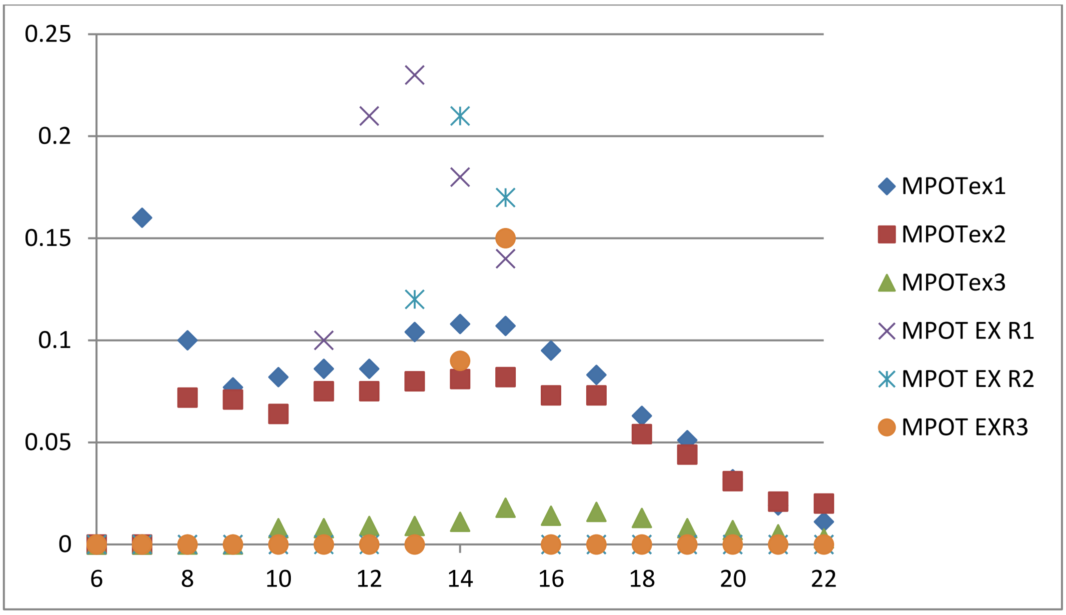

Figure (8) Experimental productivity (kg)

The production time span of the three stages was shown to the first case was broader than the previous research productivity. That was due to several reasons, the important role of preheating water before the experimental day. and the role of the tank insulated thermally made the water supplied always hot, which led to increase the first stage temperature quickly at the beginning of operation and continued temperatures for all stages were high throughout the operation, making productivity continuous. Two reasons had made the first case productivity outweigh. The rate of improvement of the production was (39.58%).

- **Theoretical productivity:**

In the beginning, the computer program was run for the theoretical readings of the previous research to verify the validity and effectiveness of the program. The error ratio between the two readings was (1.8%).

8.3. The second case:

This case included the addition of palm leaf to the first stage basin. This case will be compared with the first case in terms of productivity and Water surface temperature for each stage.

- **Total Productivity:** By studying Figure (9)

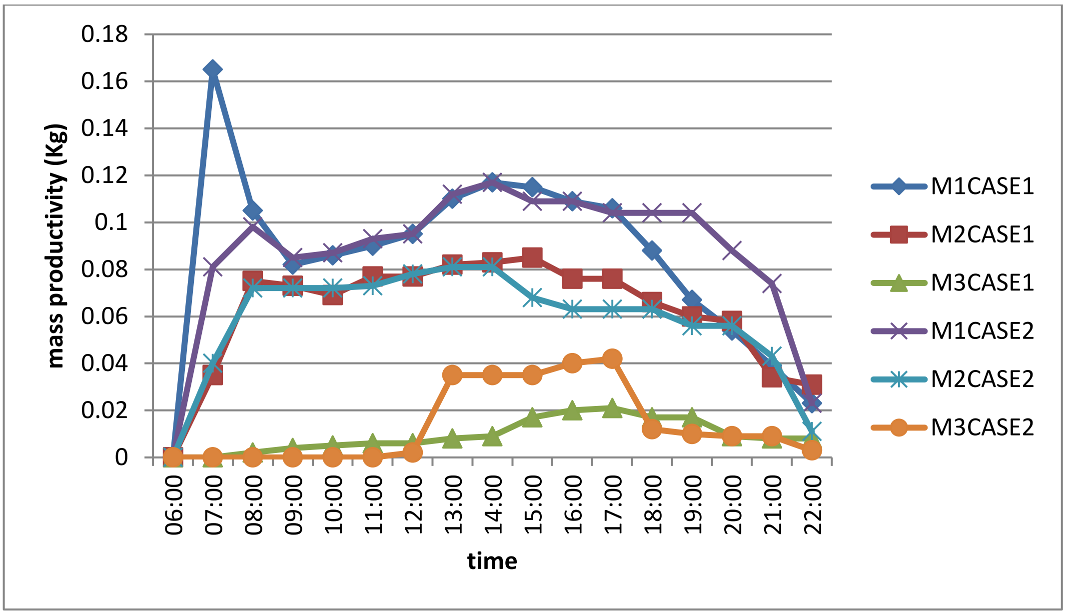

Figure (9) the theoretical productivity of the first and second stages

In the first stage, the productivity of the second case was lower than in the first case, and the highest productivity in the first case at (7:00 am) in the second case the highest productivity was at (8:00 am) , the reason was that the heating inside the solar still basin was in two stages first heating the fiber palm then warm the water inside the basin, then the productivity of the two cases converges. After (7:00 pm), the second case yield was higher than the first case this was due to the heat storage by palm fiber. In the second stage there was a marked convergence between the two cases. The productivity of the third stage in the second case started at (12:00pm) at a high rate and started to increase to reach the highest possible at (5:00 pm) after which began to decrease.

- **Night productivity:**

This productivity extended from sunset time from (7:00 pm) to (10:00 pm) as in Figure (10)

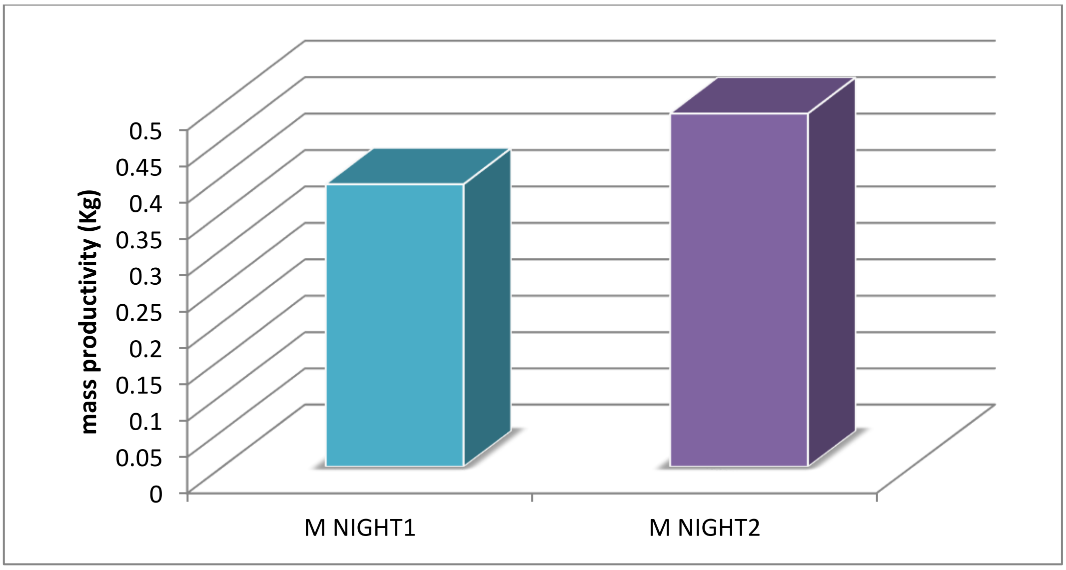

Figure (10) Night productivity

- **Water surface temperature:** By studying Figure (11)

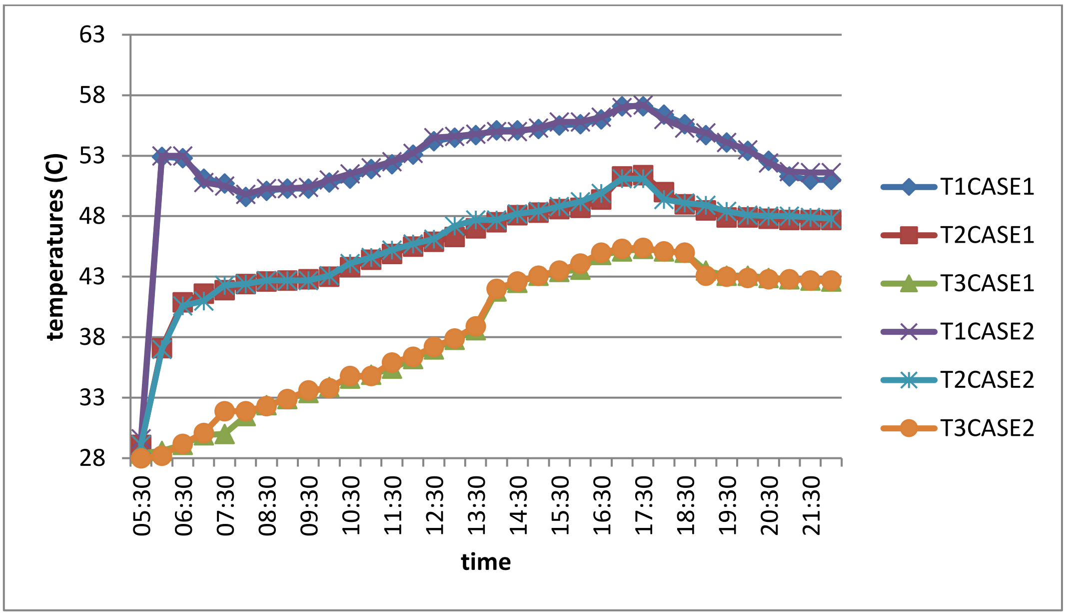

Figure (11) Water surface temperature

The coincidences at Water surface temperature gave the productivity of the two cases almost identical.

8. Conclusion:

The study was conducted in the Baghdad, capital of Iraq.in this study, a multi-stage solar still connected to an (Evacuated Solar Collector Tubes). Two cases were used, one of which was the first stage basin containing only water and the other was added the palm leaf to the basin. There are several points that summarized the results of the experimental work as follows.

1. The output of this type of solar still is higher than the output of a single solar still.
2. The output of this type of solar still is higher than the output of Common types of multi-layer solar stills
3. The daily productivity of the two cases when the basin is empty or contains the fiber is very close.
4. The night productivity of the solar still with the presence of fiber overcame the output of the still when is empty about (25%).
5. Pre-heating of water, before the day of the experimental work which was the main source of heat for the evaporation process in this type of stills, a key role in increasing productivity.
6. Water was used in this study with high TDS (425 mg/l), water produced in the first case with TDS (125 mg/l), the water produced in the second case was TDS (33 mg/l).

CONFLICT OF INTERESTS.

- There are no conflicts of interest.

Reference:

[1] 1.D.P. Kothari, K.C. Singal, Rakesh Ranjan, “Renewable Energy Sources and Emerging Technologies“, Second Edition, PHI Learning Private Limited, Delhi, 2014.

[2] Maha Rahman Rahi, “Enhancement the Performance of Passive Multi Stages Solar Still by using Parabolic Trough Collector”, M.Sc. Thesis, Tikrit University, 2016.

[3] Obaid younas, Fawzi Banat, and Didarul islam, “Seasonal behavior and techno economical analysis of a multi-stage solar still coupled with a point-focus Fresnel lens”, Desalination and Water Treatment, VOL:1944, PP 1-14, 2015.

[4] P. Patel, Solanki, A. S , Soni ,U. R and Patel A. R , " A review to increase the performance of solar still make it Multi-layer " , International Journal Recent and Innovation Trends in computing and communication , Vol. 2. pp 173-177, 2014.

[5] Jagannath S. Gawande, Lalit B. Bhuyar, and Samir J. Deshmukh., "Effect of depth of water on the performance of stepped type solar still" , International Journal of Energy Engineering, Vol. 3. pp 137-143, 2013.

[6] Kumar, P. V, Kaviti , A.K, Prakash, O.m, and Reddy ,K.S., "Optimization of design and operating parameters on the year round performance of a multi- stage evacuated solar desalination system using transient mathematical analysis", International Journal of Energy and Environment. Vol.3. pp 409-443, 2012.

[7] Mahmoud, I.M. Shatat, " New and renewable energy and environmental engineering” M.S.C Thesis, Durham University, PP. 64-65, 2008.

[8] Cooper, P. I., "The Absorption of Radiation in Solar Stills." Solar Energy, Vol.12. pp 333-346. 1969.

[9] Eames, I. W, Maidment, G.G, and Lalzad, A. K. "A theoretical and experimental investigation of a small-scale solar – powered barometric desalination system". Applied Thermal Engineering, Vol. 27.pp 1951-1959. 2007.

[10] Fernandez, J. and Chargoy, N, "Multi-stage, indirectly heated solar still". Solar Energy,Vol. 44. pp 215-223. 1990.

(دراسة عملية ونظرية لمقطر شمسي متعدد الطبقات متصل بانابيب مفرغة مجمعة للطاقة الشمسية)

منتظر هاشم عبد　　منى صباح قاسم　　فؤاد علوان صالح

قسم الميكانيك، كلية الهندسة، الجامعة المستنصرية، بغداد، العراق

foads2003@yahoo.com　munasaljabri@gmail.com　engmuntadher.alsafi1987@gmail.com

الخلاصة:

التقطير الشمسي أحد الحلول الفعالة والمفيدة لحل مشكلة شحة المياه النقية على سطح الارض. استعمل مقطر شمسي متعدد الطبقات وتم تحسين ادائه من خلال ربطه بانابيب مفرغة لتجميع الطاقة الشمسية. فكانت نسبة الزيادة بالانتاجية عن الانواع الاخرى بنسبة (38%). اجريت دراستان عملية ونظرية لحالتان الاولى كانت باحتواء خزانات المقطر الشمسي على الماء فقط من دون اي اضافة اما الحالة الاخرى فكانت باضافة ليف النخل الى حوض المرحلة الاولى. اضافة ليف النخل حسن من الانناجية الليلية للمقطر فكانت نسبة الزيادة في الانتاجية الليلية حوالي (25%) عما هو فارغ.

يعتبر هذا النوع من المقطرات الشمسية تقنية حديثة في تحسين اداء المقطرات الشمسية متعددة الطبقات.

الكلمات الدالة: مقطر شمسي، التقطير الشمسي، ليف النخل، متعدد الطبقات.