The Effect of Extended Surfaces on the Heat and Mass Transfer in the Solar Distillation Systems

Yusuf Bilgiç[#1], Cengiz Yıldız[#2]

[#] *Mechanical Engineering Department, Firat University, 23279, Elazig, Turkey*

***Abstract*— Various methods are used for obtaining drinking water from salt water. One of these methods is the distillation of the salt water by solar energy. In this work, the effect of extended surfaces in a solar-still system is investigated experimentally. Two distillers are constructed to use in experimental works. One of these distillers is conventional distiller and used as a reference. The other distiller is used to investigate the effect of extended surfaces. The experiments are carried out in Elazığ/Turkey climate conditions. In the experiments, Climate conditions (Solar radiation, wind speed, environmental temperature), Glass cloth temperature, distiller pool temperature, base temperature, distiller side wall temperature and the amount of distilled water are measured and evaluated. To extend the surfaces, table tennis balls with diameters of 40 mm, which are painted black, are used. To move the balls in the distiller, the salt water is sprayed from sides by a circulating pump.**

In the experiments, the amounts of distilled water are compared for stationary and moving balls. Obtained results show that extended surfaces improves the efficiency of distillation system.

***Keywords*— Solar Energy, Solar Still, Solar Distillation.**

I. INTRODUCTION

Fresh water constitutes 3% of world water reserves. By this amount it is not possible to meet the water need of rapidly growing population. One of the ways to meet the need is to obtain fresh water by distillation of salt water. For this purpose, numerous distillation processes have been developed. It is possible to discuss such processes by categorizing them in three groups, e.g. fossil fuel, nuclear fuel and renewable energy. The most widespread use of the distillation systems basing on renewable energy is solar distillation.

A review of the literature showed that there are both experimental and theoretical studies on solar stills. Most of those studies are related to enhancement of the performance of solar stills. Conventional solar still consisting of double-condensing chamber was used by Asgarwal and Tiwari [1,2], and an increased output by 46% compared to the single-effect still was achieved. Abu-Arabi et.al. [3], have also investigated the performance of double-gloss cover cooling solar energy.

Toure and Meukam [4] have experimentally examined digital modelling of a solar still. It was observed that when the water depth was increased from 5 mm to 60 mm, a reduction occurred in the output by up to 19%, and when wind speed was increased from 0 m/s to 9 m/s, an increase occurred in the output by 10%.

Aboul-enein, et.al. [5] studied on the single-basin solar still by considering the effect of the depth of basin On a single-pool solar energy still, glass thickness of 3 mm, glass angle of 15o, insulation thickness of 0.075 and surface area of 1 m2 were defined as the optimum values .

El-Sebaii et.al [6] has studied performance of a single-basin solar energy still with suspended absorbent surface made of different layers throughout one year. As a result of experiments conducted, they determined daily productivity of 20% for aluminium, 17.2% for copper and 17.2% for stainless steel. Furthermore, they observed that when mica was used, the productivity was increased about 23% compared to copper and that the solar still with suspended absorber is more productive than the conventional by 42%.

El-Hinai and El-Nassri Yurban [7] have discussed how climate, design and operating parameters can affect the production of a simple solar still. They found out that the maximum production realized at 13:50 as 0.5kg/m2. They determined that the maximum production was in June, e.g. 6.78 kg/m2 and the minimum production was in December, e.g. 3.17 kg/m2. With ambient temperature increased from 23oC to 33oC, the production increased by 8.2%.

El-Sebaii, Aboul-Enein and El-Bialy [8] have studied single-basin solar still where suspended absorbent surface is used. In the study, they observed that the effect of the hole area on the daily production is inversely proportional and that while the hole area increased from 0,00 m2 to 0,20 m2, the amount of distilled water produced reduced from 5,177 to 4,099 kg/m2 per day. They concluded that optimum position of the suspended screen for productivity in the middle of salt water.

Solar still where floating perforated black plate was developed by Nafey et. al [9]. They found out that, by using perforated black plate on the solar still, productivity increased by 15% when water depth was 3cm, and by 40% when it was 6cm in depth. Valsaraj [10] developed a still by using a sheet, folded, perforated, coated by black and floating over the water and thus obtained a production increase of 43% in the water 90mm in depth.

Abdel-Rehim and Lasheen [11] have made to modifications for the solar still system. In the first modification, they laid a layer of glass balls 13.5 mm in diameter on the bottom of the basin to improve efficiency of the still. At the second modification, they laid a shaft rotating in the water of the basin. When they compared efficiency of the systems, they observed the efficiency as follows: packed>rotating shaft system>conventional system. They also observed change of efficiency by month, e.g. July>June>May.

Rahim [12] studied on a new method for storage of heat energy in the solar still positioned horizontally positioned. Using a black-painted aluminium plate floating on the water in the basin, he achieved storage of more heat. He recorded mean efficiency as 57% and maximum efficiency as 62%.

Tripathi and Tiwari [13] have studied effect of water depth on the internal temperature and mass transfer in the active still. They observed that efficiency of the active system was higher than that of the passive system, presenting such an effect on the heat transfer and mass transfer that, with the reduced depth of water, amount of water to be produced has increased.

In this study, a new type of still is designed where salt water is evaporated in a still system and the water thus evaporated condenses on the glass cover, accumulating outside the still through collection channels.

II. Experimental Setup

This study aims at improving efficiency of the solar stills. For this purpose, expanded surfaces were used. During experiments, 2 stills of single-basin and single-inclined type, equivalent to each other in terms of manufacture, we used. First one of these stills is conventional system. The other one is a still on which various parametric modifications were made with heat transfer surface area on it was expanded for increase of fresh water quantity to be produced in a period of 24 hours. The solar stills used in the experiments are shown in Fig.1.

Fig.1: Photograph of the experimental solar stills

Stills used in the tests had area measured as 1000mm x1000 mm. Fig.2 shows the schematic diagram of the solar still. The still case was made of galvanized sheet. For insulation purpose, glass wool in thickness of 10mm was used. The glass used as top cover was 3mm in thickness with an inclination angle of 35 degrees. Seal was used for sealing the top covers. Furthermore, in order to prevent any leakage from the glass backward the collection channel, this part was sealed by liquid seal. For accumulation of the condensate steam, a collection channel was used, 2cm in width, 20mm in height with inclination angle of 5 degrees. To prevent contact of the collection channel with sunlight, that part of the channel facing outside the channel was covered by aluminium tape. Inner side of the still was painted by black colour, resistant against water and high temperature. For the expanded surface, 200-400-600 balls painted black in colour were used. Fig.3 shows photograph of extended surfaces solar still.

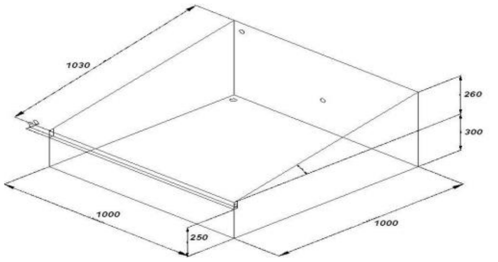

Fig.2: Schematics of the solar still.

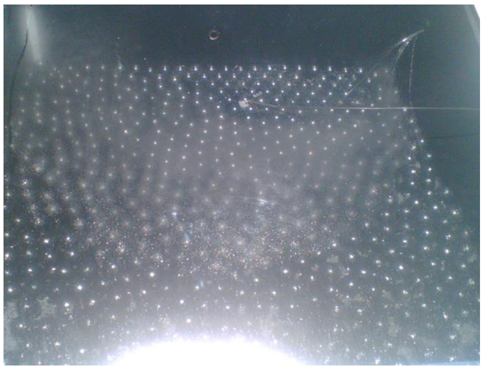

Fig.3: Photograph of extended surfaces solar still

25W water pump was used to move the balls inside the still. A control circuit as shown in the Fig.4 was designed to adjust automatic stop and operating times of the pump. In this circuit, the circuit elements shown by legends of ZR1 and ZR2 are multi-functional time relays. These relays can be adjusted between 1s and 30 hours. The circuit element shown by the legend M in the circuit is contactor.

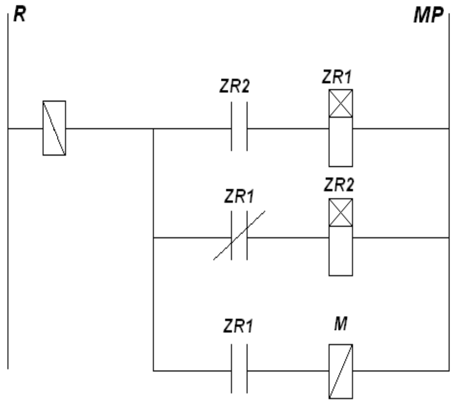

Fig.4: Schematics of Control circuit

For ensuring movement of the balls, both ends of the ½” polypropylene pipe were sealed and sprayer with holes of 2mm in diameter drilled by interval of 1cm was used. This sprayer was installed at water level.

In the still with expanded surface, number of balls was increased by 200 for each test. In this system, the balls are submerged into the water halfway the volume of them. A circulation pump was used to move these submerged balls. Pump was connected to a control unit controlled by time relays. Thus the pump stops for 90 seconds and operates for 10 seconds. The pump sprays the hot water in the still through a drain valve again to the side of the balls, causing a circular and reciprocating motion of the balls. In order to spray water on the balls, a sprayer with holes of 1 mm in diameter was used. Glass wool was wrapped around the hose and pipes to prevent heat loss of the circulation line. Fig.5 shows schematics of the extended surfaces solar still.

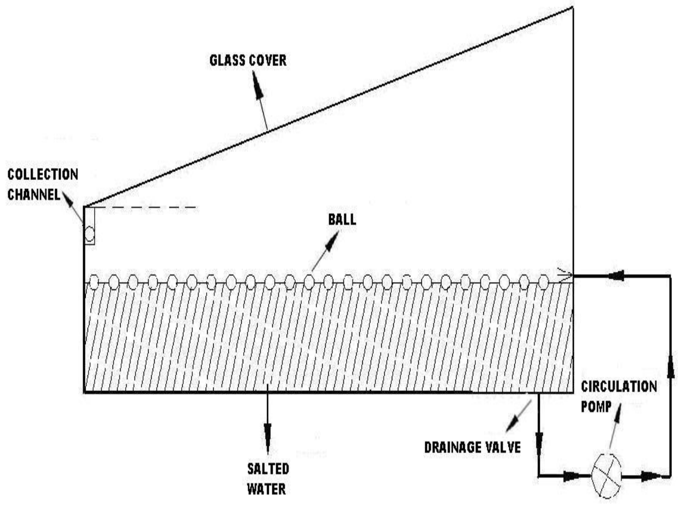

Fig.5: Schematics of the extended surfaces solar still.

For determining amount of solar radiation, Kipp and Zonen brand (CC12) pyranometer was used. Pyranometer was installed with a parallel inclination to the system. Temperature was measured by Elimko branded digital thermometer and channel selector by using 5mm K type iron-constant thermal couple. Thermocouples were connected to 18 points from the evaporation part of the basin, top of and under the glass on 4 side walls and bottom of the still and in the basin water, and, a further one was used to measure ambient temperature. For measurement of instantaneous wind speed, Lutron AM-4201 anemometer with accuracy of ±0,1 was used. In order to measure amount of distilled water from the collection channels, a measure of 5000 cm^3 was placed at the exit points.

In the conventional system, 100kg water in height of 10cm was used. Salt water in the still evaporates by help of the surface absorbing solar radiation and, after contact with the glass surface, condenses and flows towards the collection channel thanks to the inclination on the glass surface. Water collected in the collection channel advances towards the exit point due to 5-degree inclination of the channel. And the distilled water flows from here to the measure.

The still was installed on the terrace in the Department of Mechanical Engineering, Fırat University (Elazığ/Turkey). The geographical position of Elazığ is 39:14E 38:41N with altitude of 1096m. The still was placed on iron feet in height of 25cm. The still was positioned facing southward.

During the experiments,, reading data were recorded every 30 minutes from the measuring instruments (pyranometer, measure, digital thermometer).

III. Results and Discussions

In this study, a new type of still is designed where salt water is evaporated in a still system and the water thus evaporated condenses on the glass cover, accumulating outside the still through collection channels. The experiments were carried out the dates of 22.07.2007 and 30.07.2007 at the city of Elazığ in Turkey.

Solar radiation values belonging to first and last days of the experiments are illustrated in Fig.8. It was measured as 649 W/m^2 at 09:00 am , 1028 W/m2 at 01:00 p.m and 369 W/m2 at 5:00 pm for the first day of the experiments.

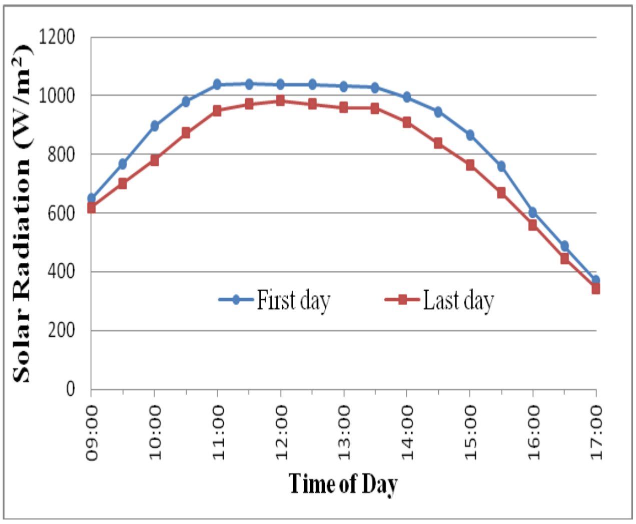

Fig.6: Variation of solar radiation for first day and last day

Lower and upper surface temperatures of the condenser glass ($T_{gb,I}$,$T_{gt,I}$,$T_{gb.II}$,$T_{gt.II}$) were transferred to the graphics (Fig.7-Fig.8). According to them, the glass temperatures increase till 16:00-16:30 and decrease afterwards. It is known that the glass temperatures have an inversely proportional effect on the efficiency in the solar stills. As you may see from the graphics, when the balls don't move, the under-glass temperatures ($T_{gb.II}$) are very higher then other temperatures.

Water temperature (Tw) and vapour temperature (Tv) are shown in the Fig.9 and Fig.10. It is seen that when the balls on the still with expanded surface are motionless, the steam temperature is much higher that the case with the conventional system, and that this temperature increases with number of the balls. The reason is that the balls do not give most of their heat to the water, but to the steam inside the still. When the balls start to move, this temperature difference starts to reduce. When the bottom and water temperatures are compared for two stills, we see comparative values close to each other.

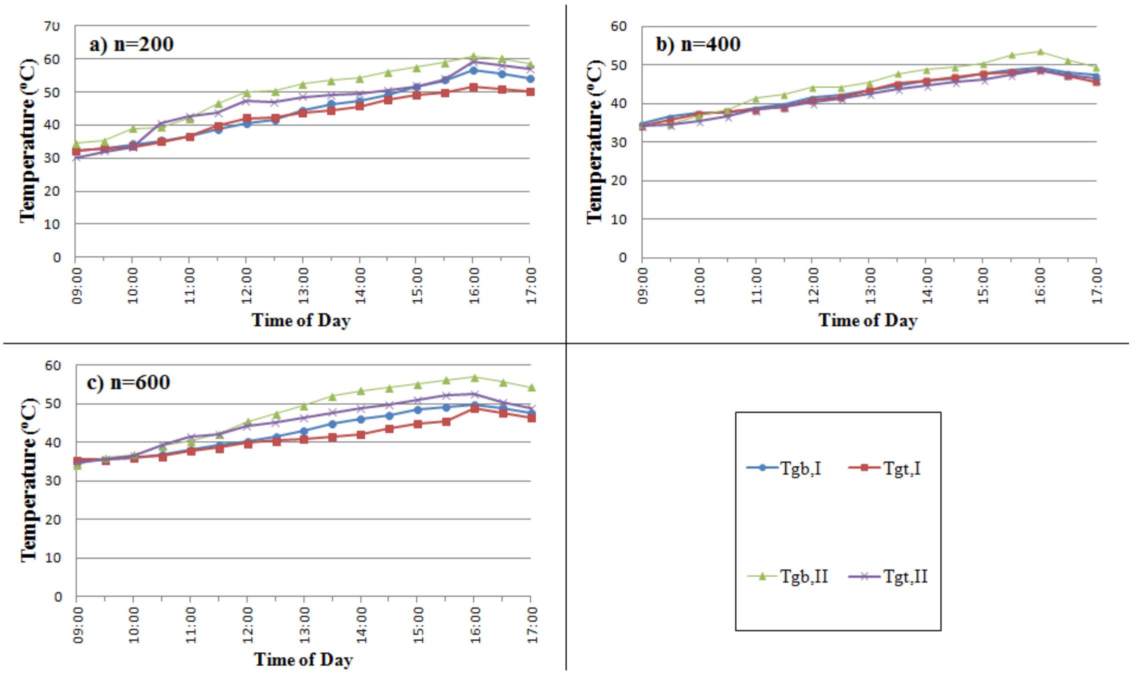

Fig.7: Variations of the temperatures of the condenser glass (for the stationary balls)

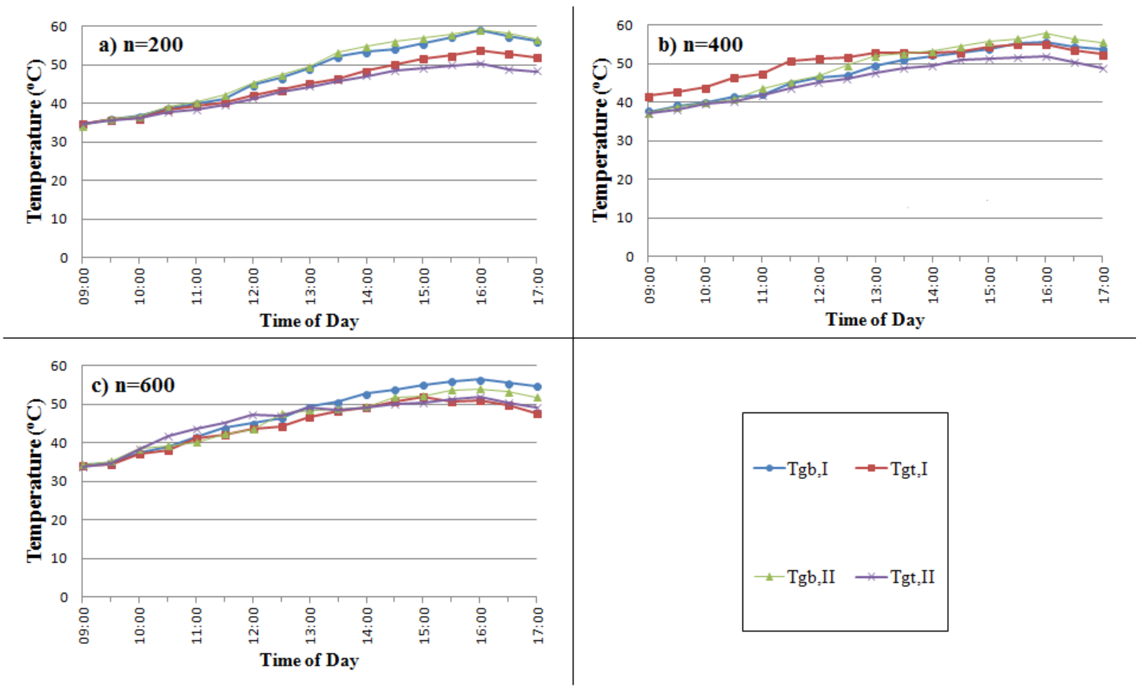

Fig.8: Variations of the temperatures of the condenser glass (for the moving balls)

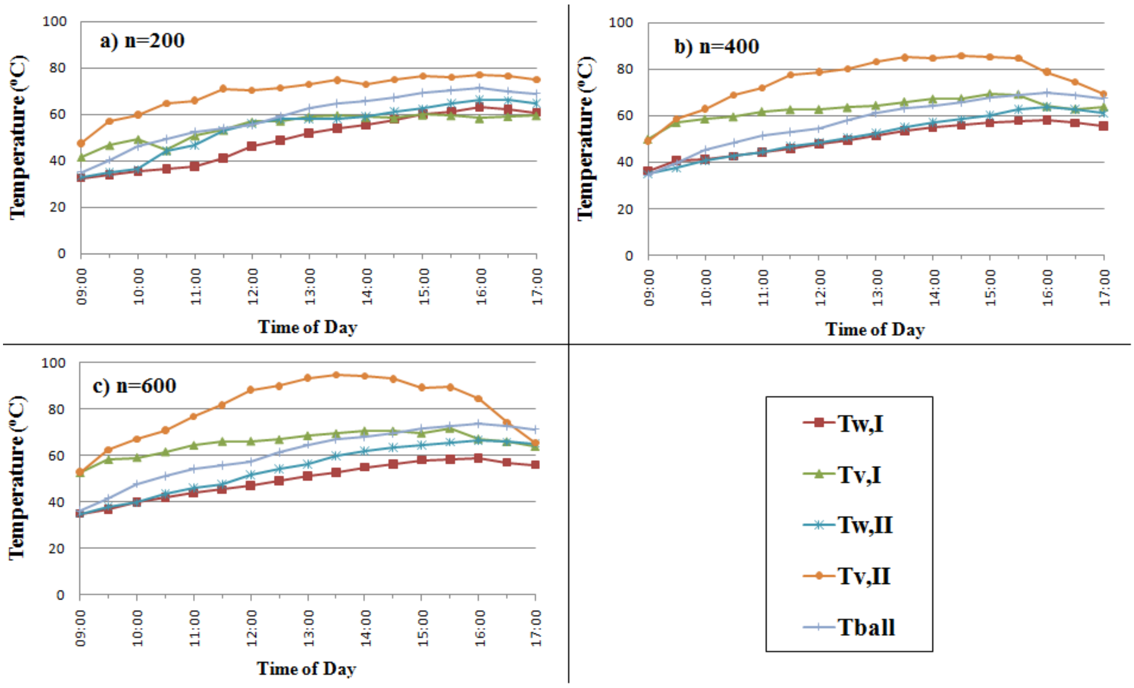

Fig.9: Variations of the temperatures of water, ball and steam temperature (for the stationary balls)

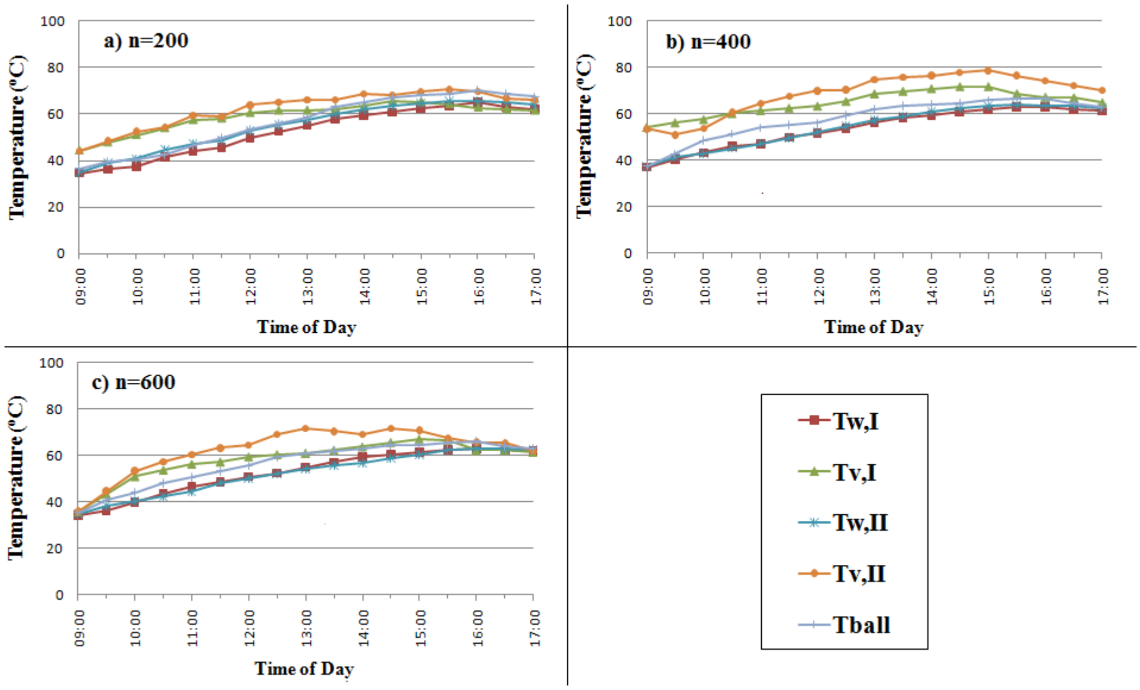

Fig.10: Variations of temperatures of water and steam temperature (for the moving balls)

Time-dependant change in the water amount produced in the still was transferred to the graphics (Fig.11-Fig.12). The amount of production in the still with expanded surface is higher than that of the conventional system when the balls are motionless. The amount of reduction increases proportionally to the number of balls. The reason is that as no evaporation occurs at such a part of the still as much as the area occupied by the balls in the still, resulting in the reduced amount of steam in the still.

Likewise when the balls move, a higher increase is observed compared to the conventional system. And the increase here is also proportional to the increase in the quantity of the balls. With movement of the balls within certain time frames, a water layer forms with a thin film on them. And this phenomenon causes increase of evaporation rate in the system. The amount of increase is related both to number of balls and waiting time of the pump. Increase in the number of balls also increases amount of evaporation. As seen in the graphics, production amount increases till 14:30-15:30 and reduces afterwards.

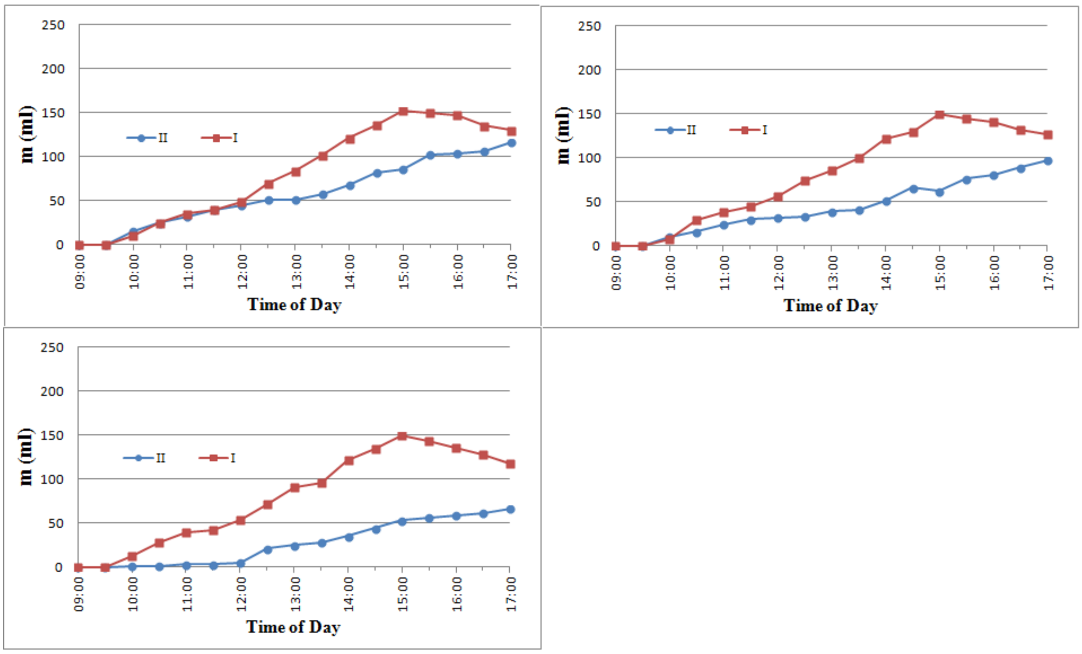

Fig. 11: Variations of hourly productivity (for the stationary balls)

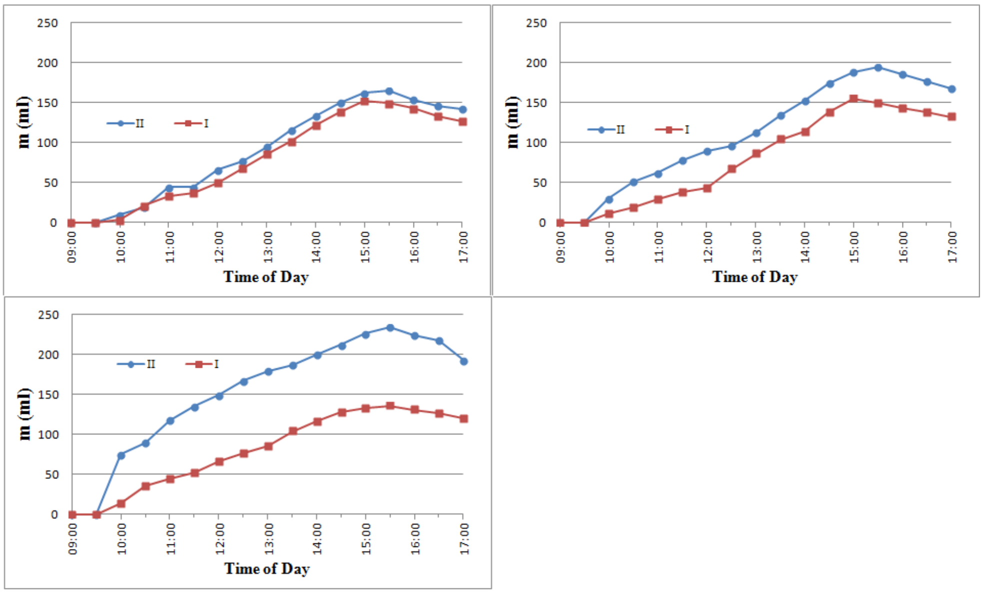

Fig.12: Variations of hourly productivity (for the moving balls)

The efficiency can be found by using the following equation for solar still [4,5]:

$$\eta = \frac{\dot{m} L_V}{IA} \qquad (1)$$

where m is output fresh water (kg/s), L_v is latent heat of evaporation of water (J/kg), I is solar radiation (J/m^2s) and A is area (m^2). The efficiency is calculated by using Eq. (1). The efficiency is a parameter depending on solar radiation, amount of clear water and amount of heat loss. Graphics indicating production efficiency obtained as a result of tests conducted are shown in the Fig.13 and Fig.14. In the state when the balls are motionless, the efficiency is less than that of the conventional system. With the balls starting to move, the efficiency increases compared to that of the conventional system. When the balls are motionless, the efficiency reduces with number of balls . When the balls start to move, the efficiency increases along the increased number of the balls.

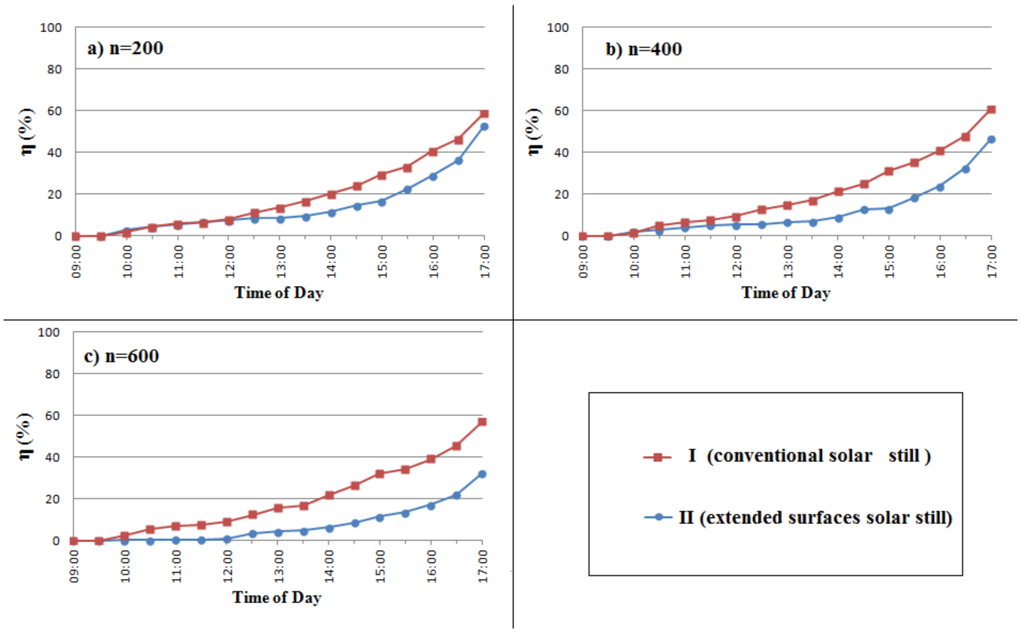

Fig.13: Variations of the efficiency of solar still (for the stationary balls)

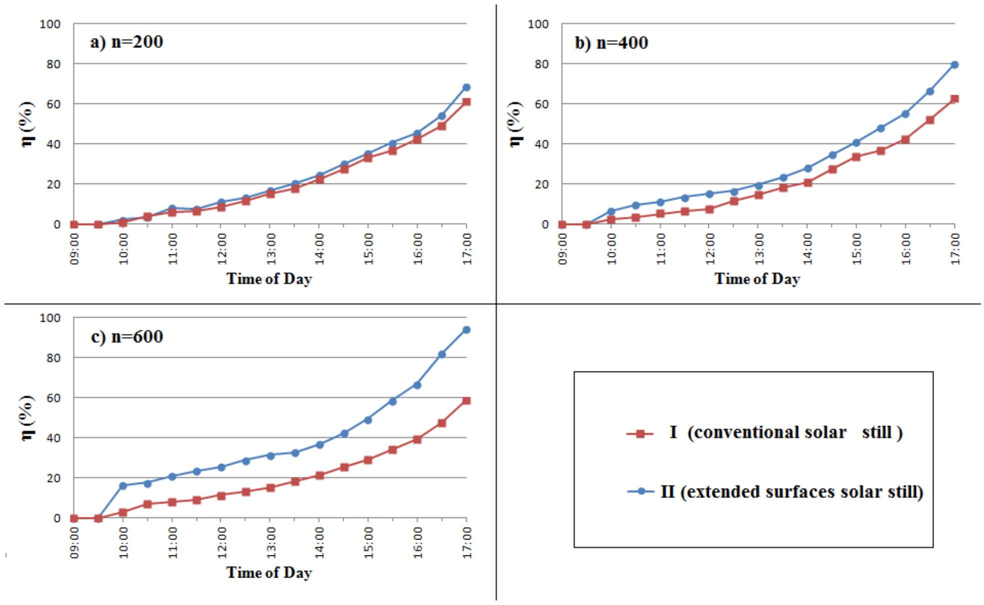

Fig.14: Variations of the efficiency of solar still (for the moving balls)

Average efficiency values and amount of distilled fresh water obtained as a result of the experiments are illustrated in Table I. Average efficiency values are evaluated by dividing sum of the average efficiencies measured between 9:00am and 5:00pm to number of the measurement which is equal to 17. In this time interval, seventeen measurements were read out. The amount of daylight production in Table 1 is a cumulative value of 8 hours between 9:00 am and 5:00 pm. Likewise, the amount of night-time production is the cumulative value of 16 hours between 5:00 pm and 9:00 am. The values in total column show the amount of fresh water per 24 hours.

Table I: Average efficiency values and amount of distilled fresh water

System name	*Number of balls*	*Situation of the ball*	*Average Efficiency (%)*	*Daytime production (ml)*	*Night production (ml)*	*Total production (ml)*
Extended Surfaces Solar Still	200	stationary	13.86	981	2587	3568
	400	stationary	11.41	747	1916	2663
	600	stationary	7.43	461	1513	1974
	200	moving	22.4	1523	2838	4361
	400	moving	27.60	1892	3368	5260
	600	moving	36.92	2607	4156	6763
Conventional system			18.76	1356	2619	3975

Change in the still with expanded surface related to the conventional system is defined by a pure number "X". Accordingly, it is calculated by the following formula:

$$X = \frac{m_{II} - m_I}{m_I} x100 \quad (\%) \tag{2}$$

where m_I is the output freshwater for conventional solar still and m_{II} is the output freshwater for extended surfaces solar still.

In the figures 15 and 16, change rates of the system with expanded surface to the conventional system are given. Here the motionless system shows reduction compared to the conventional system with the most reduction occurs daytime. The amount of reduction increases along with the increased number of the balls. In the still with expended still, on the other hand, this rate increases along with the number of balls. And in this system, the increase mostly occurs daytime. Like the motionless system, the rate of change is directly proportional to the number of balls.

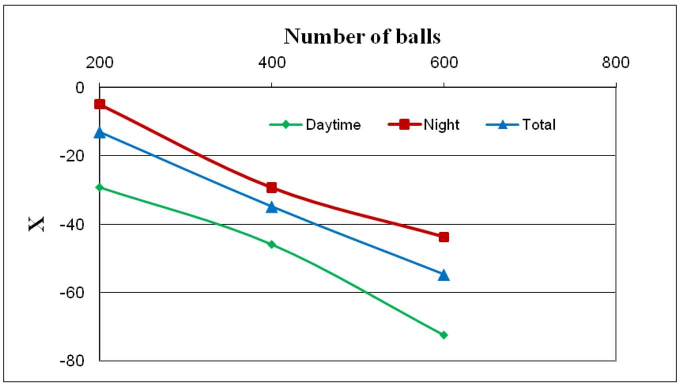

Fig.15: Comparison of productivity rate between conventional system and distiller with stationary balls

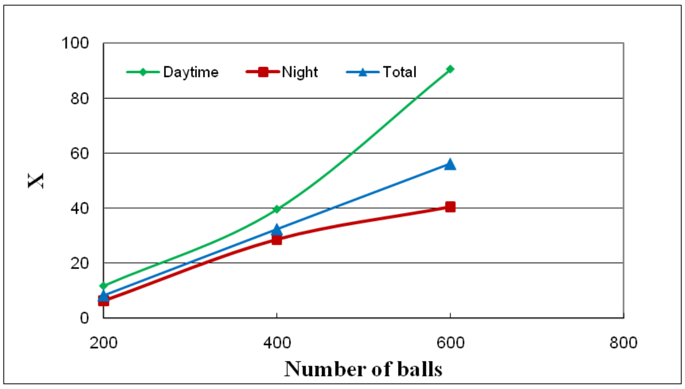

Fig.16: Comparison of productivity rate between conventional system and distiller with moving balls

IV. CONCLUSIONS

In order to change surface area in the system, balls 40mm in diameter were used. These balls were examined when they are in motion or motionless with the following conclusions:

1. In the motionless system, tests were conducted by using 200-400-600 balls in number. It was observed that steam temperature and temperature under the condenser glass were higher than other temperatures. Productivity and efficiency was found out to have reduced when number of balls was increased. Efficiency was 52.65% in case of 200 balls and the maximum efficiency went down to 32% when 600 balls were used.
2. In the moving systems, tests were performed by using 200-400-600 balls in number. It was observed that productivity and efficiency increases proportionally to the increased number of balls. Upon movement of the balls, water temperature increases. And the moving balls make positive effect on the mass transfer, increasing evaporation as well. As a result of tests performed, it was observed that while maximum efficiency was 68.27% when 200 balls were used, it was 94.17% when 600 balls were used. It was also found out that the maximum efficiency obtained in this system when 600 balls were used was 6763 ml.

3. Compared to the solar still, the total production amount in the still with expanded surface increased by 57% by use of 600 balls.
4. It was observed in the process of distillation that while productivity was minimum in the morning, it realized maximum between the hours 15:00-16:00.

It is concluded that use of moving and expanded surfaces for distillation of water is more appropriate than conventional systems.

NOMENCLATURE

T_w : Temperature of water (^oC)
T_v : Temperature of the vapor (^oC)
T_{ball} : Temperature of the ball (^oC)
T_{gb} : Temperature of the bottom surface of the glass (^oC)
T_{gt} : Temperature of the top surface of the glass (^oC)
m : Productivity (ml)
n : Number of the balls
η : Efficiency of the productivity (%)
I : Conventional Solar Still
II : Extended surfaces solar still

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