PERFORMANCE STUDY ON REDESIGNED TUBULAR SOLAR STILL

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ABSTRACT

Solar distillation is a natural technology which is now becoming a promising method of purifying water. It can extensively be used for practical purposes, particularly in the remote or coastal areas of underdeveloped and developing countries where there is a scarcity of drinking water due to contamination of salts and other impurities. To minimize the production cost of solar distillation, tubular solar still (TSS) is used worldwide. In this study, a TSS is successfully redesigned and constructed on the roof of the Civil Engineering Departmental building of Khulna University of Engineering & Technology (KUET) consisting of a rectangular trough (40 inch long, 8 inch wide, 2.5 inch deep) made of i) a 1 inch thick ferro-cement material, ii) GI wire and wire mesh and a transparent cover using 5 nos.- 2.75mm thick semi-circular SS wire. The outer side and bottom of the tray is painted with a heat resistant paint to minimize the heat loss. The field experiment is conducted from 27th May, 2015 to 24th August, 2015. But due to cloudy weather in July-August, the daily production rate is calculated for the month of May-June neglecting the lower values (smaller than 0.9 Lit/m^2-day) which is 1.62 Lit/m^2-day (0.330 Lit/day). The production cost of distilled water is estimated as 0.34 Tk./Lit. It is found that the production rate is increased 4% due to use of the paint. The results presented in this study give clear information to understand the behavior of production rate, production cost etc. for TSS.

Keywords: *Tubular Solar Still (TSS), heat resistant paint, transparent cover, drinking water, production rate*

1. INTRODUCTION

Remote and arid to semi-arid regions depend on underground water for drinking. Unfortunately, underground water is not always considered to be fresh drinking water. In some instances, the salinity is probably too high for water to be considered as fresh drinking water instead it is called brackish water. The salinity of brackish water varies with location. In such cases, fresh water has to be either transported for long distances or connected with an expensive distribution water network at extremely high cost for, usually, a small population (Bilal et al., 1999). Most of the rural areas in the world are deprived of adequate sanitary infrastructure. Poor wastewater management practices in rural areas often aggravate environmental pollution. In any community, aggregation of sanitary wastewater is inevitable and wastewater aggregation is the basic cause of water pollution which, in turn, causes diseases in remote areas. Thus wastewater discharges to the surface water are now critical in many parts of the world and will be increasingly important in the future (Benschine et al., 2002). Again, many remote and coastal areas of underdeveloped and developing countries don't have enough resource of electric power for producing distilled water using any conventional water desalination techniques; namely multi-effect distillation, multi-stage flash, reverse osmosis, vapor compression etc. The initial installment cost of these techniques is very expensive too. In addition, a water distribution system is not available in these regions, and the road network and transportation system are insufficient to carry/transport water in large volume regularly. For the above reasons, solar distillation is most suitable and required immediately in these regions. The development of desalination plants in recent years and the estimation of increased trends in desalination directions are increasing the interest in understanding desalination plants currently in use. The cost of desalinated water is still high for many people, so there is a need to learn how to reduce costs as well as understand how the techniques work before trying to develop new technologies. The demand for fresh water has increased significantly since 1990 for many reasons, including, on the one hand, the increase in world population accompanied by the increase in standards of living, and, on the other hand, global warming followed by climate changes and desertification. Governments and water industries are seeking different solutions for better utilization of available water, thereby increasing the efficiency of growth crops, solutions for better wastewater treatment, and the development of new water sources and improved desalination techniques. Many desalination techniques were considered over the years. Some survived the economic battle and are currently in use in different places around the globe. Others did not make it, yet are being reviewed from time to time in order to seek possible better techniques (Awerbuch, 1997).

Solar distillation is the oldest method to produce potable water from brackish or saline water by utilizing the solar energy as reported by various researchers. It is more economical in the areas receives more solar radiation and better solution to the problem of energy security and climatic change with zero running cost. A solar still is defined as a green energy process that uses the free natural energy of the sun to purify contaminated water to produce clean water. The solar still process uses the solar energy instead of other sources of energy like fossil fuels, oil and gas to gain the energy needed for purification. Solar distillation technology has a long history. Documented use of solar stills began in the sixteenth century. An early large-scale solar still was built in 1872 to provide drinking water to a mining community in Chile (Ismail, 2009). Solar stills mimic the natural process: when water evaporates, the still removes only pure water and leaves all contaminants behind (Thomas et al., 1990). Solar stills use solar energy for heating water, and therefore, there is no additional need for energy use. The energy is free and available in almost every location and is environmentally friendly. Solar still has been used in locations where the other types of energy resources are inadequate, treatment options are not available and sunshine is abundant. There are many advantages to using solar still technology: a solar still has no moving parts, and the used energy is renewable, free and clean. Solar still uses simple technology that requires a simple design and less manufacturing, operation and maintenance capabilities, therefore, based on the low-technology requirements, the requirement of large land areas and the high requirement for manual labor, solar stills are ideally suited for use in developing countries or in remote locations (Radhwan, 2005). Solar energy can be used to recover pure water from available saline water; however, the use of solar distillation for sewage and industrial wastewater purification is not yet well known. The objectives of the study are to redesign and construct a low cost Tubular Solar Still (TSS) using locally available materials and to carry out field experiment on the top roof of the Civil Engineering building of Khulna University of Engineering & Technology (KUET) from 27th May, 2015 to 24th August, 2015 to analyze the performance of the TSS.

2. METHODOLOGY

2.1 The steps of the methodology are as follows:

- Redesign of TSS.
- Construction of TSS.
- Conducting field experiment.
- Data Collection
- Data Analysis
- Estimation of production
- Estimation of production cost
- Comparison of results with non-painted TSS (Habib, 2015)
- Concluding remarks.

3. ILLUSTRATION ON DESIGN, CONSTRUCTION, FIELD EXPERIMENT AND DATA ANALYSIS

3.1 Redesign of the Tubular Solar Still

The previously designed TSS is consisted of a transparent tubular cover and a black rectangular trough for storing saline water inside it. The Tubular frame is 1.05mm long, 300mm in diameter and comprised of 2.75mm thick G.I. wire. The trough is 1m long, 200mm width, 63mm deep and made of 25mm thick ferro-cement material. The distilled water is collected in a PET bottle and the bottle is kept in an insulation box. The schematic diagram of this type of TSS is shown in the Figure 1.

The redesigned TSS also consists of a rectangular trough (1m long, 200mm width and 63mm deep) made of 25mm thick ferro-cement material and a transparent cover using 5 nos.– 2.75mm thick semi-circular wire (Figure 2). Here 5 nos. semi-circular SS wires are used instead of circular wires that have been fixed in the extended part on both sides of the tray. The outer side and bottom of the tray is painted with a heat resistant paint to minimize the heat loss.

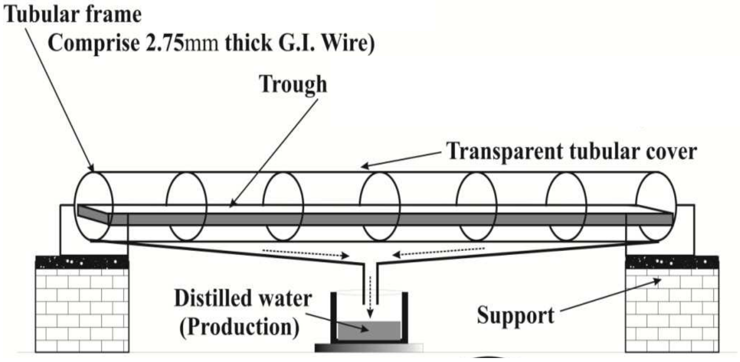


Figure 1: Schematic Diagram of Previously Designed Tubular Solar Still

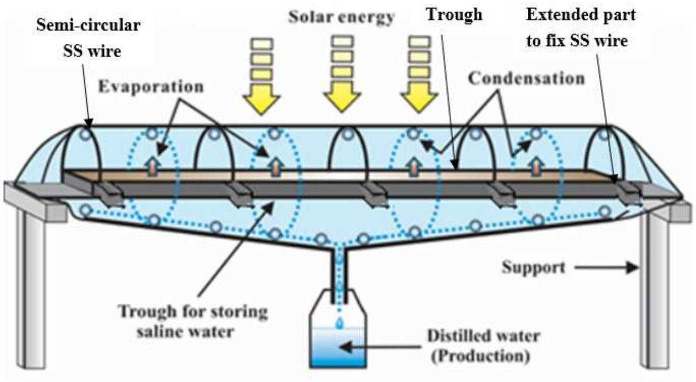
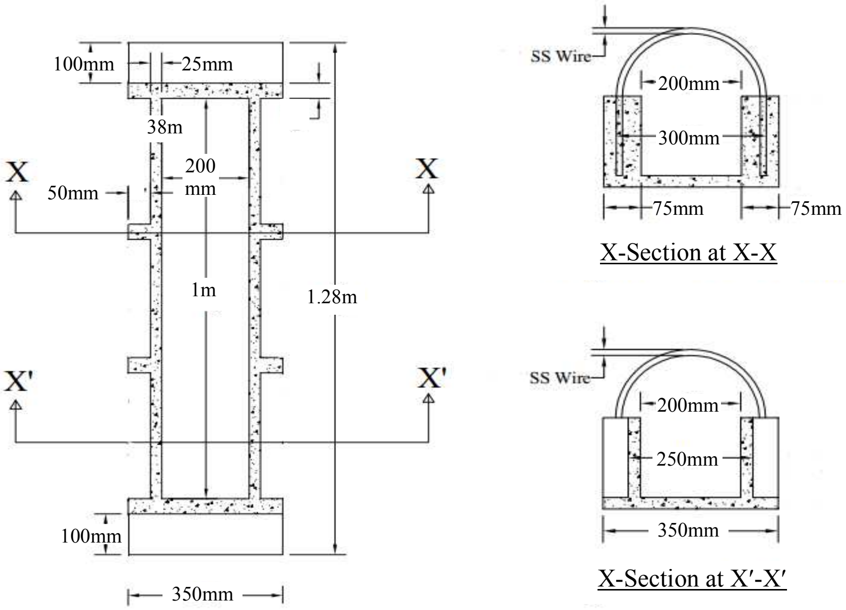


Figure 2: Elavational Diagram of Redesigned TSS



X-Section at X-X

X-Section at X′-X′

Figure 3: Schematic diagram of the tray

3.2 Construction of the Tubular Solar Still

The tray of the TSS is consisted of 25mm thick cement-sand mortar centrally reinforced with locally available GI wire mesh sandwiched with #8 gauge GI wire in both direction. For sides of the trough, #10 gauge GI wire is used to keep the GI wire mesh in position. Ratio of cement-sand mortar is uesde as 1 cement**:** 2 local sand by weight. In addition, the bottom and outer side of the tray of the TSS is painted with a heat resistant paint to minimize the heat loss. Then the constructed tray is placed on brick walls so that space for the collection pipe can be provided beneath the still. After that the cover is made by the semi-circular SS wire and transparent polythene. A PET bottleis used to collect the distilled water. The collection bottle is fixed with brick barrier. The cross-section of the tray of the TSS with reinforcement detailing is shown in Figure 4.

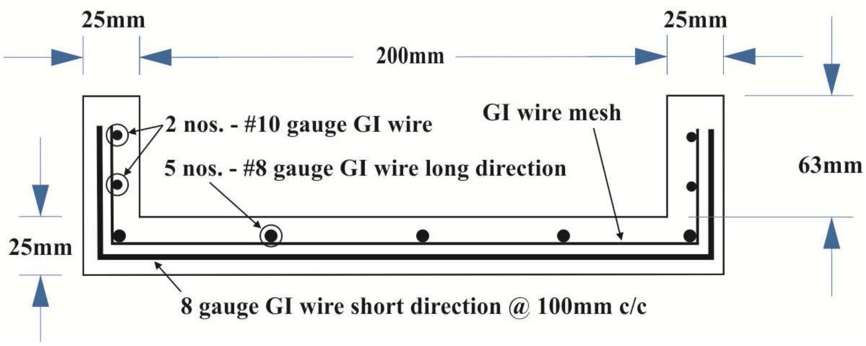


Figure 4: Cross-section of the tray of the TSS with reinforcement detailing

3.3 Field Experiment

The constructed TSS is set on roof of Civil Engineering building and field experiment is conducted from 27th May, 2015 to 18th August, 2015. A pyranometer is used to measure the solar radiation flux, whereas two thermo-couples are used to measure the air and water temperatures. A data logger TDS-303 is used to measure the solar radiation flux and temperatures data at 2 minutes interval. Figure 5 shows the photographs of the field experiment. Hourly productions on August 19 and 24 are also recorded.

Figure 5: Photographs of the field experiment

3.4 Data Collection

The daily distilled water output data is collected from the TSS everyday approximately two hours after the sunset in the study period. Table 1 shows the daily production of distilled water of the TSS in the study period. Hourly productions on August 19 and 24 are also recorded and shown in Table 2.

Table 1: Daily distilled water production from 27th May to 18th August, 2015

Day	Daily Distilled Water Production (Lit/day) in 2015			
	May	June	July	August
1	-	0.38	-	-
2	-	0.37	-	-
3	-	-	-	-
4	-	0.35	-	-
5	-	0.36	-	-
6	-	0.37	-	-
7	-	0.28	-	0.21
8	-	-	-	-
9	-	0.34	-	0.37
10	-	0.3	-	0.25
11	-	0.38	-	0.23
12	-	0.31	-	-
13	-	-	-	0.08
14	-	0.29	-	0.16
15	-	0.30	-	0.11
16	-	0.28	-	0.16
17	-	0.29	-	0.15
18	-	0.33	-	0.09
19	-	-	-	-
20	-	0.36	-	-
21	-	0.32	-	-
22	-	0.29	0.07	-
23	-	0.31	0.06	-
24	-	-	0.07	-
25	-	0.35	0.05	-
26	-	0.39	0.06	-
27	0.31	0.30	0.05	-
28	0.29	0.37	0.08	-
29	0.27	0.36	0.08	-
30	0.34	-	-	-
31	0.07	-	-	-

Table 2: Hourly distilled water production, air, water temperature and solar radiation flux on August 19 and 24, 2015

Time of Day	Hourly Distilled Water Production (ml/hr)		Air Temperature (^{O}C)		Water Temperature (^{O}C)		Solar Radiation Flux (W/m^{2}-^{0}C)	
	August 19	August 24	August 19	August 24	August 19	August 24	August 19	August 24
6:00 AM	-	-	-	26.8	-	-	-	-12.6
7:00 AM	-	-	-	27.9	-	-	-	71.9
8:00 AM	5	7	-	29.1	-	-	-	224.8
9:00 AM	9	12	-	29.6	-	-	-	350.8
10:0AM	15	21	-	30.6	-	-	-	570.7
11:0AM	18	23	34.4	31.5	45.9	-	277.1	176.1
12:00PM	19	29	31.8	31.8	45.4	-	414.5	497.7
1:00 PM	36	38	31.3	32.5	44.8	-	395.3	378.3
2:00 PM	34	39	31.4	31.9	44.5	-	228.4	479.9
3:00 PM	31	33	31.1	31.0	47.6	-	286.1	271.6
4:00 PM	32	31	30.8	31.2	44.0	-	140.6	231.1
5:00 PM	30	28	30.4	30.8	40.0	-	-2.8	72.7
6:00 PM	21	18	29.7	30.0	36.3	-	-12.3	4.0
7:00 PM	10	12	29.6	30.2	33.3	-	-25	-20.8
8:00 PM	-	5	29.2	28.9	31.6	-	-20	-15.2

3.5 Data Analysis and Results

The daily (from 27th May, 2015 to 18th August, 2015) and hourly (August 19 and 24, 2015) distilled water production per unit surface area of the saline water in the trough are calculated and given in Table 3 and 4, respectively.

Figure 6 shows the variation of the daily production rate throughout the study period. It is found that the production rate is higher in the month May-June and lowers in the month July-August. It is seen from the figure that the production rate decreases gradually from May to August. The maximum output is recorded as 1.92 Lit/m^2-day (0.390 Lit/day). Figure 7 shows the variation of the daily output for the month May-June. The average output for the month May-June is found as 1.445 Lit/m^2-day (0.293 Lit/day) and can be expressed by the linear regression equation given by Equation (1). To estimate the average output, all outputs below 0.9 Lit/m^2-day which are got due to cloudy weather, are excluded.

$$y = 1.9268 - 0.0215x; \quad (r^2 = 0.98) \tag{1}$$

Where, y = production rate of distilled water (Lit/m^2-day)
x = rank of the day in which 1 for May 27 and 60 for August 18

Table 3: Daily production rate from 27th May, 2015 to 18th August, 2015

Day	Daily Distilled Water Production (Lit/m^2-Day) in 2015			
	May	June	July	August
1	-	1.87	-	-
2	-	1.82	-	-
3	-	-	-	-
4	-	1.72	-	-
5	-	1.77	-	-
6	-	1.82	-	-
7	-	1.38	-	1.03
8	-	-	-	-
9	-	1.67	-	1.82
10	-	1.48	-	1.23
11	-	1.87	-	1.13
12	-	1.53	-	-
13	-	-	-	0.39
14	-	1.43	-	0.78
15	-	1.48	-	0.54
16	-	1.38	-	0.79
17	-	1.43	-	0.74
18	-	1.62	-	0.44
19	-	-	-	
20	-	1.77	-	
21	-	1.57	-	
22	-	1.43	0.34	
23	-	1.53	0.30	
24	-	-	0.34	
25	-	1.72	0.25	
26	-	1.92	0.00	
27	1.53	1.48	0.30	
28	1.43	1.82	0.25	
29	1.33	1.77	0.94	
30	1.67	-	1.33	
31	0.34	-	-	

Table 4: Hourly distilled water production, air and water temperature and solar radiation flux on August 19 and 24, 2015

Time of Day	Hourly Distilled Water Production (Lit/m^2-hr)		Air Temperature (^{O}C)		Water Temperature (^{O}C)		Solar Radiation Flux (W/m^2-^{0}C)	
	August 19	August 24	August 19	August 24	August 19	August24	August19	August 24
6:00 AM	-	-	-	26.8	-	-	-	-12.6
7:00 AM	-	-	-	27.9	-	-	-	71.9
8:00 AM	0.025	0.035	-	29.1	-	-	-	224.8
9:00 AM	0.045	0.06	-	29.6	-	-	-	350.8
10:0AM	0.075	0.105	-	30.6	-	-	-	570.7
11:0AM	0.09	0.115	34.4	31.5	45.9	-	277.1	176.1
12:00PM	0.095	0.145	31.8	31.8	45.4	-	414.5	497.7
1:00 PM	0.18	0.19	31.3	32.5	44.8	-	395.3	378.3
2:00 PM	0.17	0.195	31.4	31.9	44.5	-	228.4	479.9
3:00 PM	0.155	0.165	31.1	31.0	47.6	-	286.1	271.6
4:00 PM	0.16	0.155	30.8	31.2	44.0	-	140.6	231.1
5:00 PM	0.08	0.14	30.4	30.8	40.0	-	-2.8	72.7
6:00 PM	0.105	0.09	29.7	30.0	36.3	-	-12.3	4.0
7:00 PM	0.05	0.06	29.6	30.2	33.3	-	-25	-20.8
8:00 PM	-	0.025	29.2	28.9	31.6	-	-20	-15.2

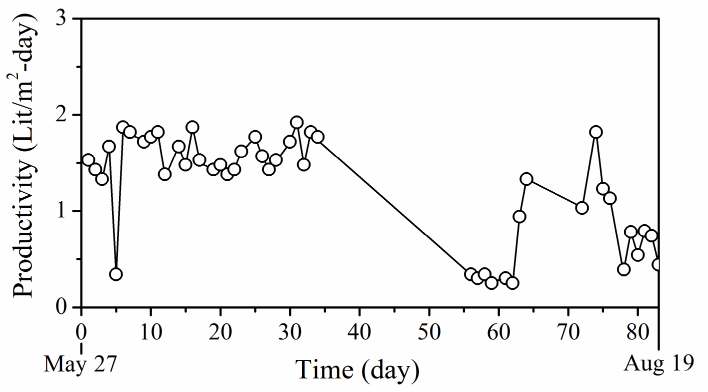


Figure 6: Daily output of the TSS for whole study period

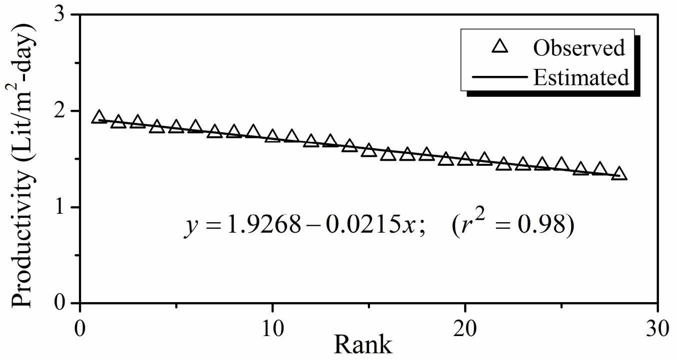


Figure 7: Daily output of the TSS for May-June

Hourly production, air and water temperature and solar radiation for a typical day (August 24, 2015) are measured from 6.00 AM to 8.00 PM at 2 minutes interval using data logger. Then the average of these readings is taken for 1 hour interval (Table 4). Then the variation of hourly production, water temperature, air temperature and solar radiation flux at 24 august, 2015 is shown in Figure 8. It is observed from the figure that the air temperature, water temperature and solar radiation flux values increase gradually from morning and these values are at peak between 11.00 AM to 1.00 PM and then decrease gradually in the afternoon. It is evident that the increment of solar radiation flux is faster than the increment of air and water temperature. The average daily production rate and average hourly production rate are found at August 24 are 0.220 Lit/day and 0.018 Lit/hr, respectively.

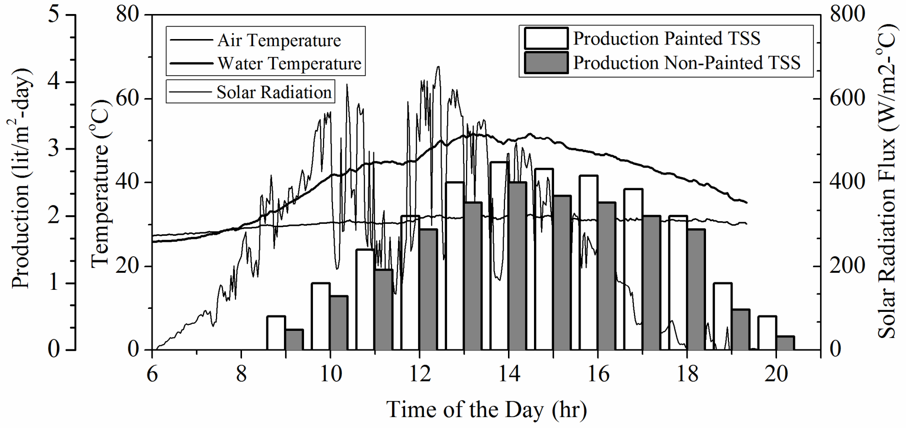


Figure 8: Variation of hourly production, water and air temperatures and solar radiation flux on August 24, 2015

3.6 Comparison between Painted and Non-Painted TSS

Number of TSS required for a family can be calculated by the following equation. The comparison of daily production of distilled water in the study period is shown in Figure 9.The maximum output of painted TSS is recorded as 1.92 Lit/m^2-day (0.390 Lit/day) which is greater than the maximum output of non-painted TSS (1.89 Lit/m^2-day). The average output of painted TSS (1.07 Lit/m^2-day) is also greater than the average output of non-painted TSS (1.03 Lit/m^2-day) which indicates that the production rate is increased 4% due to use of the paint. Figure 10 and Figure 11 show the comparison of hourly distilled water from the TSS with and without painting which also indicate the average hourly output of painted TSS is also greater than the average output of non-painted TSS.

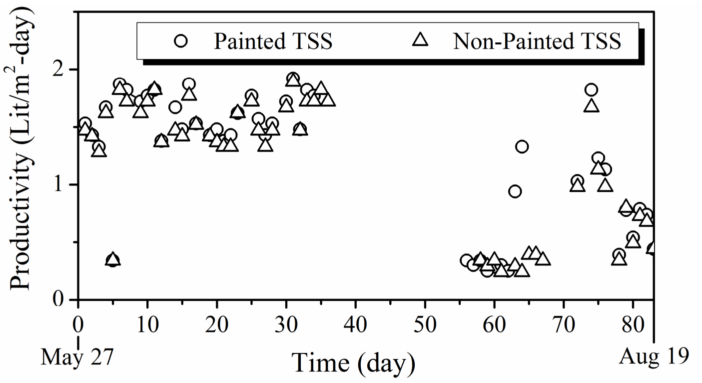


Figure 9: Comparison of daily distilled water production between the painted & non-painted TSS throughout the study period

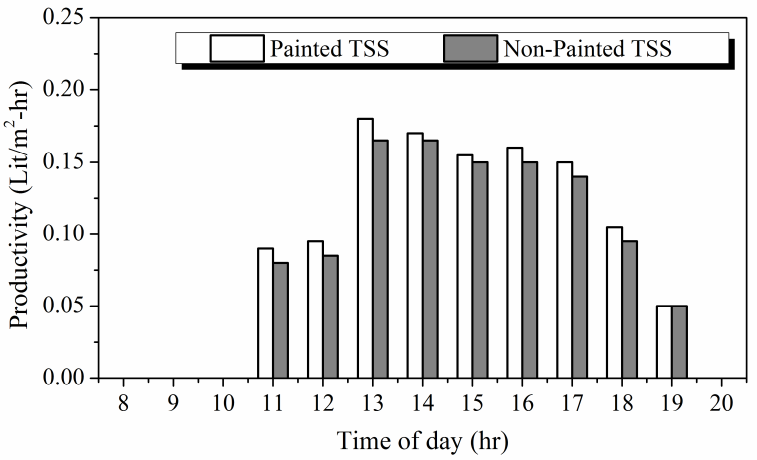


Figure 10: Variation of hourly production of the TSS with and without paint on August 19, 2015

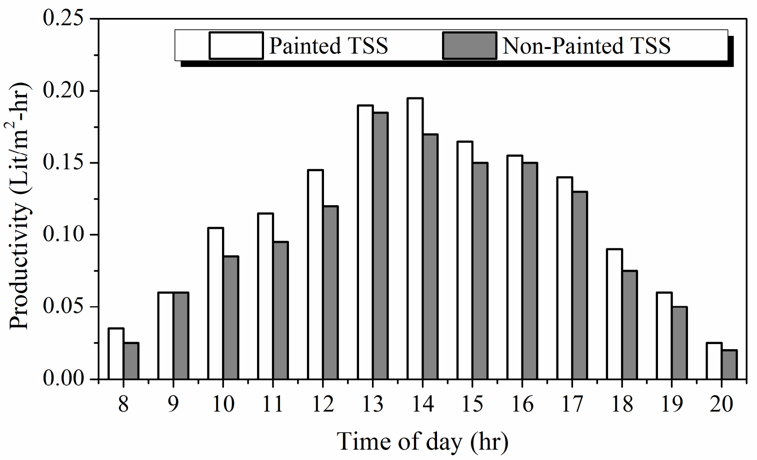


Figure 11: Variation of hourly production of the TSS with and without paint on August 24, 2015

Table 5 and Table 6 show the average and peak production rate from 27th May, 2015 to 18th August, 2015for the redesigned TSS. The average production rate throughout the study period is found as 1.07 Lit/m^2-day (0.22 Lit/day) for painted TSS and 1.03Lit/m^2-day (0.209 Lit/day) for non-painted TSS respectively.

Table 5: Summary of average and peak production rate in each month for the TSS with painting

Month	Average Production Rate (Lit/m^2-Day)	Peak Production Rate (Lit/m^2-Day)
May	1.26	1.67
June	1.63	1.92
July	0.51	1.33
August	0.89	1.82

Table 6: Summary of average and peak production rate in each month for the TSS without painting

Month	Average Production Rate (Lit/m^2-Day)	Peak Production Rate (Lit/m^2-Day)
May	1.23	1.62
June	1.57	1.89
July	0.49	1.23
August	0.82	1.67

Figure 12 and 13 show the average monthly and peak monthly production of distilled water in Bar Charts. The average distilled water production rates are maximum in June (1.63 Lit/m^2-day and 1.57 Lit/m^2-day for the TSS with and without painting, respectively).

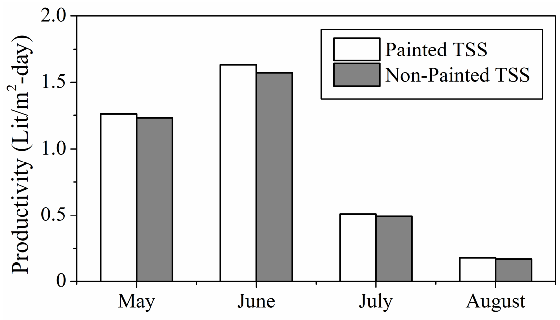


Figure 12: Variation of monthly average production rate

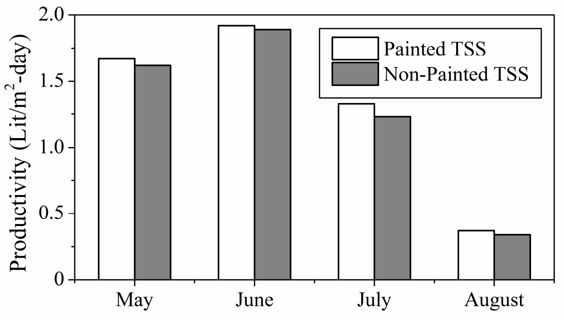


Figure 13: Variation of monthly peak production rate

3.7 Cost Analysis

Table 3.7 shows the cost estimation for the redesigned TSS. The production cost of the water is estimated as 0.34 Tk./Lit.

Table 3.7: Cost Analysis for the TSS

Item Description	Unit	Rate (Tk.)	Quantity	Amount (Tk.)
G.I. Wire	Kg	70	0.7	49
Wire Mesh	sft	10	3	30
Cement	Kg	9	5.6	50
Sand	cft	25	0.28	7
Polythene	m	25	1	25
Paint	Lt	85	0.15	12
Miscellaneous	--	--	--	10
			Total =	183

Design life = 10 years.
Construction cost = 183 Tk.
O&M cost throughout design life = 100 Tk.
Avg. distilled water production = 1.07 Lit/m^2-day
Total water production in design life = 794 Lit.
Production cost of water = 0.34 Tk./Lit.

4. DISCUSSION

The aim of the study is to get pure water from the waste water through using the redesigned TSS. It is more economical in the areas receives more solar radiation and better solution to the problem of energy security and climatic change with zero running cost. Many remote and coastal areas of underdeveloped and developing countries don’t have enough resource of electric power for producing distilled water using any conventional water desalination techniques of high initial installment cost. In addition, a water distribution system is not available in these regions and the road network and transportation system are insufficient to transport water in large volume regularly. For the above reasons, solar distillation is most suitable and required immediately in these regions. Truly speaking, solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible, and where the water scarcity is severe. The only disadvantages of TSS are: the output of solar still depends on the climate, thermal, still design or other related technical factors, its efficiency is not so good, can't work at night, slow process in comparison to reverse osmosis due to use of solar energy only. Considering all these matters, a TSS is redesigned, constructed with low cost and locally available materials additionally using i) semicircular SS wire in the upper part of the cover; ii) heat resistant paint at the outer side and bottom of the tray to minimize the heat loss and iii) GI wire and wire mesh with other local materials to fulfil the requirements of reinforcementwhich increase the durability than previously designed TSS and so the probability of crushing is minimized. Readings are also taken from a non-painted TSS for performance comparison. Then field experiment is conducted on the roof top of the Department of Civil Engineering at Khulna University of Engineering & Technology, Khulna from 27th May, 2015 to 24th August, 2015.The average daily distilled water production rate of the TSS having paint to minimize heat loss is observed as 1.07 Lit/m^2-day (0.220 Lit/day) and the production cost is estimated as 0.34Tk./Lit which can be considered as a little better TSS than the TSS without painting whose production rate and cost are found as: 1.03 Lit/m^2-day (0.209 Lit/day) and 0.35 Tk./Lit respectively. It is found that the production rate is increased 4% due to use of the paint.

5. CONCLUSIONS

The construction cost of each TSS and also production cost of distilled water from the TSS is found very low. Hence, it could be used as a low cost medium for providing the safe drinking water especially in arid and coastal areas.

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