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DEVELOPMENT AND PERFORMANCE ANALYSIS OF A DOMESTIC SOLAR STILL

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ABSTRACT

Potable water is a basic need for the habitants of an area. In Pakistan, almost 53% of total population does not have access to safe and sufficient drinking water because of brackish/saline water. The brackish/saline water could be economically desalinized by solar desalinization (distillation). To solve this problem, a solar still was designed, fabricated and installed at Agricultural and Biological Engineering Institute, National Agricultural Research Centre, Islamabad. The solar still was developed with mild steel sheet having 2 m^2 area, the inlet water depth was kept 2 cm, angle of glazing (glass) was kept 15^0, and the basin base was painted black to absorb the solar radiation. The performance of the solar still was evaluated from June to December, 2011. The parameters measured/calculated were: ambient temperature, inlet water temperature, vapours temperature, basin water temperature, basin temperature, wind speed, solar radiation, and productivity (output) of the solar still. The average daily productivity of the solar still for months of June, July, August, September, October, November, and December was 5738 ml, 3937 ml, 2637 ml, 1837 ml, 2082 ml, 1620 ml, and 1510 ml, respectively. The productivity of the solar still was higher during the month of June (5738 ml) as compare to its productivity during the month of December (1510 ml), this was because of higher solar intensity during the month of June. The average productivity of solar still from June to December was 3000 ml and the overall efficiency was 22%. The average cost of desalination was predicted Rs. 3.9 per litre.

Keywords: potable water, solar water desalination, saline water, typical day.

INTRODUCTION

Potable water has so much importance that access to a better quality drinking water supply is not only a basic need and precondition for a healthy life; it is also a human right. Water is the main part of all the life cycles of living things. However, about 1.1 billion people, who are a large fraction of the World's population, do not have access to better or microbiologically safe water source for drinking (WHO, 2002).

In Pakistan, only 23.5 percent in rural areas and approximately 30 percent in urban areas have access to safe and sufficient drinking water and can use their source of water without endangering their health (Rosemann, 2005). General public, in Pakistan, use poor quality water like brackish, foul smelling, bad tasting, turbid or coloured water which is not suitable for drinking. The unavailability of drinkable water in large parts of Balochistan, Sindh and Southern Punjab is a critical issue. Out of all water resources in Pakistan 50% are of good quality. Underground water exists, but in some areas it is highly saline due to the presence of sodium chloride and other salts (PCRWR, 2004). Solar energy can very effectively and economically be used to convert this available saline water into potable water.

Solar distillation is an affordable and reliable source for safe water. Distillation has long been counted as a method of making saline or brackish water drinkable and purifying water in remote areas. Solar stills, operating on saline or brackish water, can ensure safe supplies of water during a drought time. Solar distillation of course uses free of cost energy to purify water than other methods. Keeping in view the above mentioned importance of solar distillation, solar desalination plants (solar stills) therefore are the feasible solution for providing sufficient amount of safe water for a small community or family in the region where sufficient amount of solar energy and access to saline or brackish water is available. The solar desalination technology is simple, low cost and low-tech, and therefore, local people can easily adopt it.

The unavailability of healthy drinking water in helpless or financially destroyed regions is increasing at an alarming rate, parallel to increasing population throughout the country. Therefore simpler and low cost methods to solve this problem are required, and the use of solar energy (free to use) for this purpose is the simpler and cheapest method relative to other processes. Solar water desalination has been practiced for many decades and different methods are being adopted for improving the efficiency of single basin solar still. For a given angle of inclination it was founded that the productivity of a solar still varies directly with the change in solar intensity or concentration. And the wind speed also greatly influenced the production and efficiency. When angle of inclination of the cover varied it gave a steady output at 15^0 at different climatic conditions (Kwach *et al*, 2010).

A solar still was constructed and studied under actual environmental conditions of Mubi, Adamawa State of Nigeria (Medugu and Ndatuwong, 2009). They performed theoretical analysis of heat and mass transfer mechanisms inside the still and carried out experimental investigations on the distillation performance of the solar still. Their experimental results correspond favourably with the theoretical analysis and reported that the productivity of the solar still increased with the intensity of solar radiation and the temperature of feed water. A complete research on water desalination and description of solar still types was given (Kudish, 1991) and suggested that the simplest and most practical design for a solar still was the single basin type. It was reported that the overall efficiency of a typical basin type solar desalination plant was 30% or lower. And also considered the effects of design parameters on the efficiency of still such as basin water depth, vapour tightness, distillate leakage, insulation, glazing material, glazing slope, and basin liner material and colour.

The importance of availability of potable water and review of the research efforts in desalination of water suggested that the solar water desalination is economical and safe method among the other water desalination processes. Therefore, this piece of research had been taken at Agricultural and Biological Engineering Institute, National Agricultural Research Centre, Islamabad. The overall objective of the study was to develop a simple device for desalination of water using solar energy, for the rural communities. However, the specific objectives were; to develop a single effect solar still that can cater the need of drinking water of a small family, to measure the performance of the still experimentally, and to perform the cost analysis of solar still in order to know the cost involved for producing a litre of distilled water.

MATERIALS AND METHODS

Development of a solar still

Typically a person drinks 8 glasses (2 litres) of water in a day, so for a small family of 3-4 members the water requirement was 6-8 litres. Cornet (2001) indicated that a 2 m^2 solar still produces 8 - 10 litres of water in a day. So a solar still of 2 m^2 area was designed to serve this purpose. The solar still was designed, fabricated and installed at Agricultural and Biological Engineering Institute (ABEI), National Agricultural Research Centre (NARC) Islamabad, at latitude 33º40' N. The specifications of the solar still were presented in Table-1 below:

Table-1. Specifications of the solar still.

Items	Values
Type	Single basin
Length (m)	2
Width (m)	1
Gross area of glazing (m^2)	1.988
Effective area of glazing (m^2)	1.912
Glazing material	Glass
Thickness of glazing material (mm)	8
Slope angle of glazing	15^0
Weight of solar still (kg)	145
Length of trough (m)	1.975
Depth of trough (mm)	25
Depth of basin water (mm)	20
Thickness of insulation (mm)	27

An isometric view was presented in Figure-1, whereas the typical view of the developed solar still was presented in Figure-2.

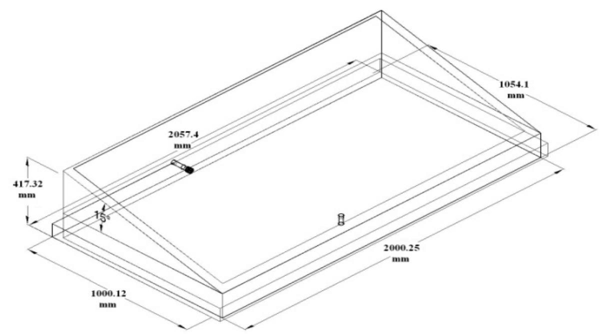

Figure-1. An isometric view of the solar still (all dimensions in mm).

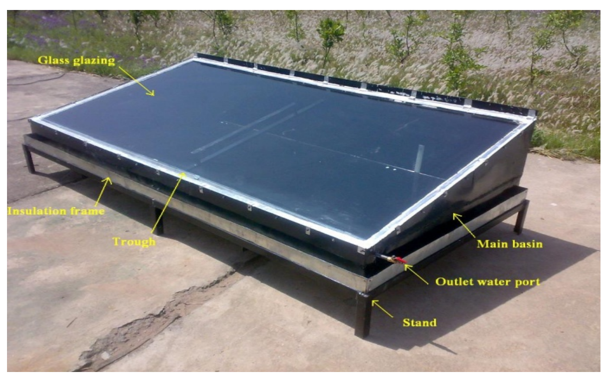

Figure-2. A typical view of the solar still showing its parts.

Methodology for measuring the performance of solar still

The performance of the still was measured at Agricultural and Biological Engineering Institute, National Agricultural Research Centre, Islamabad by measuring/calculating the ambient air temperature, temperature of water vapors in the solar still, basin water temperature, and the basin bottom temperature were recorded with the help of thermocouples. Tilt angle of glazing adjusted 15^0 with angle finder. The solar radiation data with respect to the location was collected from NARC weather station. The solar still was filled up to 2 cm depth. Productivity of the still (litres/day) was measured by using calibrated jar. Overall efficiency of the still was then calculated by ratio of productivity multiplied by latent heat

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of vaporization, to the cumulative solar radiation incident during the time period of interest (usually a day).

$$\text{Efficiency } (\eta) = \frac{\text{Productivity (Q) x Latent heat of vaporization } (\lambda)}{\text{Solar radiation (H)}}$$

Where

η = efficiency of the solar still (%)
Q = productivity of the solar still (ml)
λ = constant for latent heat of vaporization of water (2260 kJ/kg)
H = hourly solar radiation (MJ/m^2)

The data were recorded for seven months (June to December) at Agricultural and Biological Engineering Institute, National Agricultural Research Centre, Islamabad. The data were taken at one hour interval from 8 am to 9 pm for the typical day of the month, and also for one day before and one day after the typical day. A typical day represented the specific day of the month for which the extraterrestrial radiation value was estimated to be the closest as the whole month average (Duffie and Beckman, 1991). The typical days for June, July, August, September, October, November, and December were 11th, 17th, 16th, 15th, 15th, 14th, and 10th of these months, respectively.

RESULTS AND DISCUSSIONS

Table-2 summarized the hourly average solar radiation values during the typical day for different months (June to December) of the year 2011. The Table revealed that the average daily solar radiation values for the month of June, July, August, September, October, November, and December were 20.81 MJ/m^2, 19.88 MJ/m^2, 18.61 MJ/m^2, 14.03 MJ/m^2, 15.5 MJ/m^2, 11.3 MJ/m^2, and 8.4 MJ/m^2, respectively. The daily solar radiation value during the month of October was greater than the month of September because during the typical days of the month of September there was abruption by the clouds and light and heavy rainfall, while the days were clear during the month of October. The effective day length for the months of June, July, and August was 11 hours, for the months of September and October was 10 hours, for the month of November was 9 hours, and for the month of December was 8 hours.

Table-2. Hourly average solar radiation for various hours of the typical days of the months (June-December) of the year 2011.

Time	June	July	Aug	Sep	Oct	Nov	Dec
	H (MJ/m^2)	**H** (MJ/m^2)	**H** (MJ/m^2)	**H** (MJ/m^2)	**H** (MJ/m^2)	**H** (MJ/m^2)	**H** (MJ/m^2)
0700-0800	0.84	0.54	0.63	0.80	0.63	0.30	0.11
0800-0900	1.42	1.15	1.14	1.08	1.26	0.81	0.41
0900-1000	1.88	1.56	1.50	1.32	1.79	1.37	0.86
1000-1100	2.34	2.16	2.20	1.56	2.06	1.58	1.14
1100-1200	2.67	2.41	2.22	1.80	2.32	1.83	1.47
1200-1300	2.74	2.63	2.21	1.87	2.32	1.96	1.52
1300-1400	2.64	2.43	2.61	2.24	2.05	1.43	1.26
1400-1500	2.31	2.44	2.13	1.73	1.45	1.03	0.95
1500-1600	1.85	2.04	1.91	0.87	1.09	0.66	0.54
1600-1700	1.26	1.46	1.31	0.59	0.49	0.36	0.14
1700-1800	0.67	0.78	0.60	0.17	0.04	0.00	0.00
1800-1900	0.19	0.28	0.15	0.00	0.00	0.00	0.00
Total	20.81	19.88	18.61	14.03	15.5	11.3	8.4

Figure-3 showed the hourly average solar radiation for various hours of the typical days for the months of June to December, 2011. It was revealed from the graph that the every month had different maximum solar radiation values and different day lengths, descending from the month of June to December. The overlapping occurs due to seasonal changes like clouds, haze, and light and heavy rainfall in weather, the maximum hourly solar radiation value achieved was 2.74 MJ/m^2 during 12:00-13:00 hours in the month of June then descending from 2.63 MJ/m^2 in July, 2.61 MJ/m^2 in August, 2.24 MJ/m^2 in September, 2.32 MJ/m^2 in October, 1.96 MJ/m^2 in November and 1.52 MJ/m^2 in December. The day length of the month was also maximum in June and minimum in December.

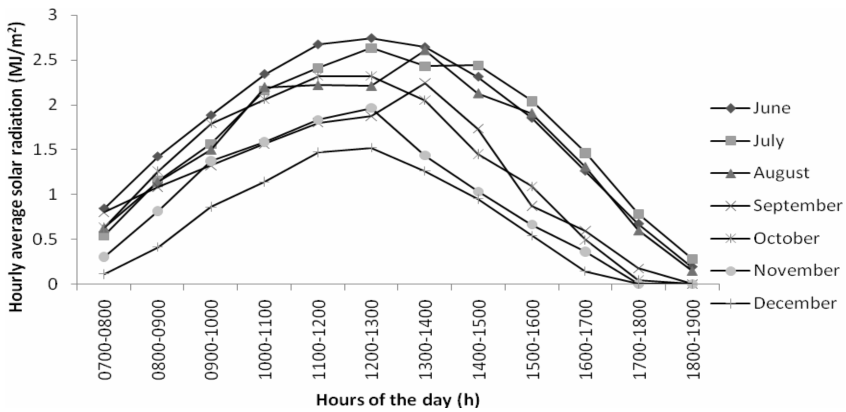

Figure-3. Hourly average solar radiations for various hours of the typical day for the months of June to December 2011.

Productivity of solar still from June to December 2011

Table-3 presented the hourly average productivity values of the solar still for typical day of different months (June to December) of the year 2011. The table also revealed that, by summing up these hourly values of the productivity of solar still, we may obtain the daily productivity values for the months (June-December) of the year 2011. This could be seen in the last row of the Table-3. The values for June, July, August, September, October, November, and December were 5738.4 ml, 3897 ml, 2637 ml, 1837 ml, 2082 ml, 1620 ml, and 1510 ml, respectively. The output during the month of October was greater than the month of September because relatively more solar radiation were received during the typical days of the month of October.

Table-3. Hourly average productivity values of the typical days for the months (June-December) of the year 2011.

Time	June	July	August	September	October	November	December
	Q (ml)	Q (ml)	Q (ml)	Q (ml)	Q (ml)	Q (ml)	Q (ml)
0700-0800	241.7	296.7	213.4	250.0	150.0	126.7	86.7
0800-0900	91.7	100.0	23.3	50.0	30.0	30.0	30.0
0900-1000	198.3	133.3	40.0	93.3	63.3	60.0	40.0
1000-1100	443.3	173.3	60.0	100.0	100.0	93.3	86.7
1100-1200	650.0	266.7	106.7	133.3	160.0	133.3	130.0
1200-1300	743.3	370.0	223.3	153.3	216.7	193.3	166.7
1300-1400	793.3	493.3	350.0	233.3	296.7	283.3	206.7
1400-1500	773.3	506.7	416.7	253.3	340.0	243.3	246.7
1500-1600	620.0	483.3	343.3	183.3	260.0	176.7	200.0
1600-1700	440.0	336.7	300.0	163.3	193.3	130.0	143.3
1700-1800	320.0	320.0	233.3	120.0	143.3	93.3	93.3
1800-1900	206.7	233.3	160.0	60.0	80.0	43.3	53.3
1900-2000	146.7	136.7	100.0	30.0	36.7	13.3	20.0
2000-2100	70.0	86.7	66.7	13.3	11.7	0.0	6.7
Total	5738.4	3937	2637	1837	2082	1620	1510

Figure-4 represents the average productivity for various hours of the typical day for the months of June to December, 2011. It was revealed from the Figure that the productivity was mainly dependent and directly propotional to the solar radiation, day length, ambient temperature and internal temperature of the still. The maximum hourly productivity gained was 793.3 ml at 1400 hours in the month of June, 506.7 ml at 1500 hours in July, 416.7 ml at 1500 hours in August, 253.3 ml at 1500 hours in September, 340 ml at 1500 hours in

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October, 283.3 ml at 1400 hours in November, and minimum 246.7 ml at 1500 hours in December. As the trend of the curves show that there was maximum quantity of output during the month of June because as discussed earlier the month of June received the maximum clear sky solar radiation intensity, ambient temperature, and the maximum day length during the typical days.

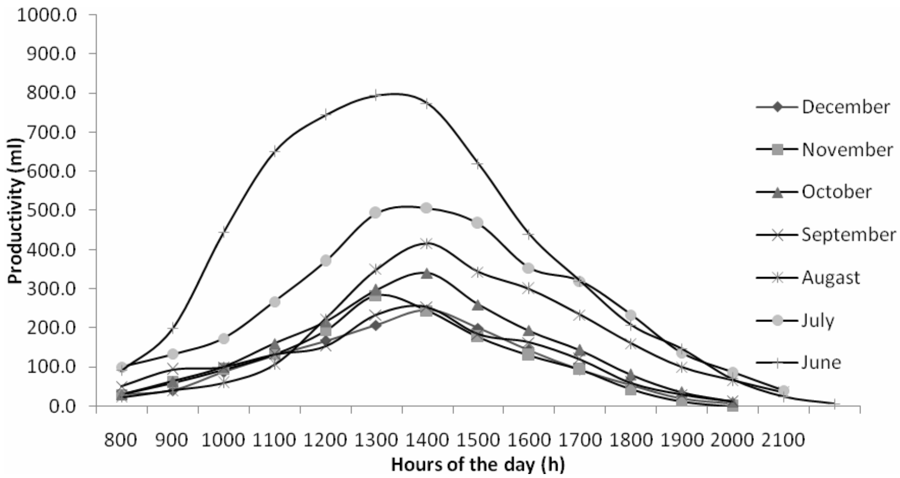

Figure-4. Daily average productivity for various hours of the typical day for the months of June to December, 2011.

Efficiency of solar still from June-December, 2011

The efficiency of the solar still for various months (June- December) is shown in Table-4. The predicted efficiency for the solar still was calculated by ratio of productivity multiplied by latent heat of vaporization, to the cumulative solar radiation incident during the time period of a day. The area of the solar still was 2 m^2, and the value of latent heat of vaporization is 2.26 MJ/litre. The efficiency of the system was greater during the month of June (31%) and fell down for the remaining months, however the efficiency was also better for the months of November and December than September and October. This was because of better productivity output in response of solar radiation values during these months. The solar still gave an average productivity of 3 litres in a day then the average efficiency of the solar still for seven months was 22%.

Table-4. Efficiency of the solar still for various months (June-December) of the year 2011.

Months	**Average daily productivity**	**Average daily solar radiation**	**Energy received**	**Efficiency**
	(litre)	(MJ/m^2)	(MJ)	(%)
June	5.7	20.81	41.6	31.1
July	3.9	19.88	39.8	22.3
August	2.6	18.61	37.2	16.0
September	1.8	14.03	28.0	14.8
October	2.0	15.50	31.0	15.1
November	1.6	11.33	22.6	16.2
December	1.5	8.40	16.8	20.3
Average	3.0	15.5	31.0	21.8

The trend of the efficiency curve for various months of the year, 2011 is presented in Figure-5. It is clear from the graph that the maximum efficiency was during the month of June, then lowered down for the months of July, August, up to September then increased again for the months of October, November, and December, showing that the productivity was better in response of solar radiation during these months.

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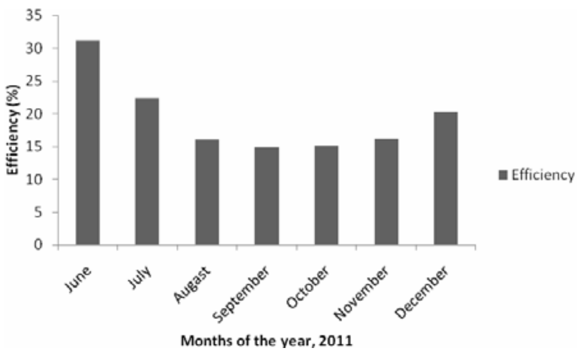

Figure-5. Efficiency of the solar still for various months (June-December) of the year 2011.

Cost analysis

Table-5 summarized the fixed cost and variable cost parameters required for calculating the cost of desalination per litre of water. The cost of the solar still was almost Rs 33040, the useful life of the system was assumed 20 years. Depreciation cost was calculated by straight line method, the interest rate was taken according to the monitory policy statement, 2011 by State Bank of Pakistan was 12%. The annual cost of repair and maintenance was assumed 2% of purchase price, so the total annual fixed cost calculated was Rs 4328. The annual distillation capacity of the solar still under consideration was predicted to be 3 litres/day, so the fixed cost of desalination of 1 litre of water was Rs 3.9. The labour requirement was almost 1 man hour a day therefore, the requirement for producing 1 litre of water reduced to 1/3 man hours, but if a family operated the solar still themselves, the labour cost could be excluded. The cost of desalination of 1 litre of water was predicted Rs 3.90. This cost of desalination using solar energy looked reasonable in remote areas of the country, where the brackish water is available for drinking. This technology may play a key role for providing the safe drinking water in these areas.

Table-5. Fixed and variable cost of solar still.

Cost parameters	**Values (PRs)**
Purchase price	33040
Useful life (years)	20
Salvage value (10% of purchase price)	3304
Fixed cost parameters	
Depreciation cost (SLM)	1487
Interest on average investment (12%)	2180
Repair and maintenance cost (2%)	661
Total annual fixed cost	4328
Annual distillation capacity of still, if 3 litres/day (litres/year)	1095
Fixed cost of distillation per litre of water	3.9
Variable cost parameters	
Labour cost (family labour)	0
Total cost (fixed + variable) (PRs/litre)	3.9
Cost per litre of water distillation	**3.9**

Therefore, the annual cost of distillation was the sum of annual fixed and variable cost. Finally, the cost of distillation of one litre of water calculated by dividing the annual total cost to the annual water distilled was PRs 3.9. The solar still of area $2m^2$, under the climatic conditions of the Islamabad, latitude 33.4^0 N could not meet the requirement of a small family, therefore; there is need to increase the area of solar still to $4m^2$ to cater the need of a small family. The solar still was also very economical in use if compared with the bottled water. The cost of one litre of water from solar still was PRs 3.9; on the other hand the bottled water costs almost Rs 26.7 per litre. The solar still on average produced 3 litres/day of water and saved Rs 68.4 on daily basis. Therefore, its payback period was worked out about 1.25 years.

CONCLUSIONS AND RECOMMENDATIONS

- The average daily productivity of solar still during typical days of the months of June, July, August, September, October, November and December were 5738.4 ml, 3897 ml, 2637 ml, 1837 ml, 2082 ml, 1620 ml, and 1510 ml, respectively.
- The average efficiency of the solar still during for the months of June to December, 2011 was 21.8%.

- The cost analysis revealed the cost per litre of water distillation with solar still about Rs 3.9, which is quite economical as compared to distilled bottled water.
- The productivity of the solar still increased with the intensity of solar radiation and energy gained from the solar radiation inside the solar still.
- The productivity of the solar still also increased with the greater ambient temperature and longer day length.
- The solar still of $2m^2$ area under the climatic conditions of Islamabad, was unable to produce the required amount of distillate, which could fulfil the drinking water requirement of a 3-4 members family. So it was recommended that area of the solar still should be at least doubled, to get the required amount of distillate (10 litres).
- The solar still was made with the mild steel sheet and get corroded after a short period of time. Therefore; it was recommended that the solar still should be made with stainless steel material to avoid rusting and corrosion. It would increase the cost but it will also increase the life of the solar still.
- The solar still should have proper insulation, so that the internal heat of the system could not escape through the body of the system by convection. Consequently, proper insulation of the solar still helped to improve the efficiency of the solar still.

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