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Solar thermal distillation of saline water through integration of vacuum tubes to solar still

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Abstract
Distillation is one of the processes that can be used for water purification. This requires an energy input, as heat. Solar radiation can be the source of energy as heat for this purpose. In this processes, water is evaporated, thus separating water vapour from dissolved matter, which is further condensed as pure water. Solar distillation is a promising alternative that can partially support the human needs for fresh water with an environment-friendly energy source. At 3 cm water depth evaporation rate was higher and hence distillate yield was found more of about 11 liters in winter. Increased salt concentration would result decrease in distillate yield. The distillate yield in lower basin was found to be maximum as the additional thermal energy was provided. Water quality analysis was carried out, it revealed that the total dissolved solids and electrical conductivity was significantly reduced after distillation and it was within the limits of WHO and BIS standards.

Keywords: solar thermal, saline water, vacuum tubes, solar still

Introduction
Water has been recognized as a basic need of human beings. Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. The availability of clean and pure drinking water is most urgent need for human community in many countries. The polluted water is not only devasting the people but also to all living things in this world [1, 2]. The excessive use of chemical fertilizers and pesticides for agriculture is also an important reason to pollute the exhausting underground water. Indian villages are posed with over exploitation of ground water due to increasing dependence on it as other fresh water resources are dwindling fast [3, 4]. This problem could be partially tackled by deriving the potable water from available brackish water with the help of technology developed on the basis of renewable energy sources.

Methodology
Design of system
Design of system has been worked out from the theoretical consideration. The input parameters for the theoretical investigation were climatic, design and operational parameters. The climatic parameters include solar intensity and ambient air temperature and these were the measured values on typical summer days having maximum intensity [5, 6]. Operational parameter includes quantity of water feed to the system. Energy balance equations were developed to evaluate the overall performance and sizing of system components. Energy balance equations were solved by elimination technique to determine the temperature developed inside the solar still and within vacuum tubes. Theoretical distillate yield was determined to calculate the base area of solar still. The designing process of solar still done according to find its optimized value to have highest amount of water productivity.
Schematic view of system is given in fig.1

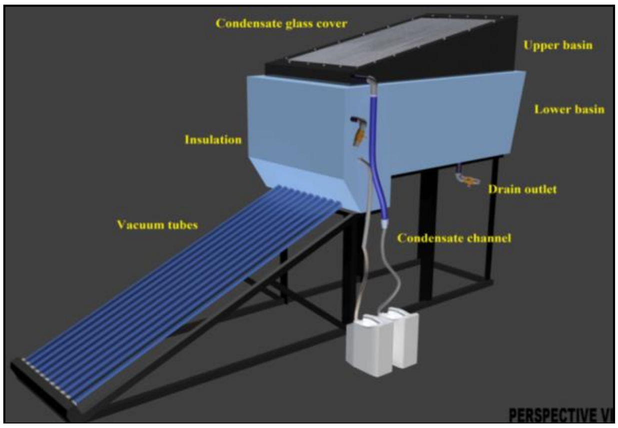

Fig 1: Double Basin Solar Still Integrated with Vacuum Tubes

Performance of the System

Performance of system depends on the climatic, design and operational parameters. The main parameter that affects the solar still performance is the mass of basin water in each effect [7]. Hence the performance of the system was evaluated at full load condition for winter and summer at 3 cm water depth. Four Different water samples from different locations were taken to study the impact of salinity of water on the performance of system. Temperature of water in lower basin, temperature of condensing glass cover surface of lower basin, temperature of water in upper basin, temperature of condensing glass cover surface of upper basin, temperature of outer glass cover were recorded with the help of calibrated thermocouples in combination with digital temperature indicator.

Water quality analysis

Water is universal solvent and contains variable quantities of dissolved solids and gases. The parameters generally used to assess water quality are pH, total salt (EC), relative proportion of cations and anions. In order to evaluate the quality of water, the different water samples were collected for analysis as given in table 1. The water samples before and after distillation then analyzed with standards given by World Health Organization (WHO) and Bureau of Indian Standards (BIS-1991). Table 2 gives the major cations and anions in water which was determined. Chemical analysis of collected water samples before and after distillation was evaluated by adopting following methodology and standard to measure is depicted in table 3

1. pH – the pH value is negative normal logarithm of hydrogen ion activity (mol/L).pH was determined using pH meter with glass-calomel electrode assembly.

2. **Electrical conductivity –** the ease with which electrical current passes through water. It is a measure of capacity of water to convey electric current. EC is proportional to salt concentration in water. Higher the EC greater is the salt concentration. EC was determined using EC meter.

3. **Total dissolve solids -** total dissolved solids (TDS) are the total amount of mobile charged ions, including minerals, salts or metals dissolved in a given volume of water, expressed in units of mg per unit volume of water (mg/L), also referred to as parts per million (ppm). The parameter TDS is given by

TDS = EC × 640

4. Sodium and Potassium – sodium constitutes 50 % or more of total cations of saline water. Potassium constitutes a small fraction of water cations. Flame photometric analysis was used for determination.

5. Calcium and magnesium – calcium and magnesium in water sample was determined by titrating it against standard EDTA solution using Black T (EBT) as indicator and NH_4OH as buffer to give pH of about 10.

6. Carbonate and Bicarbonate – sum of carbonate and bicarbonate ions constitutes to be total alkalinity of water as temporary and raises its pH to more than 7.5. Carbonate and bicarbonate ions in the sample were determined by titrating it against standard sulphuric acid using phenolphthalein and methyl orange as indicators, respectively.

7. **Chloride** – Mohr's titration method is most commonly used for chloride estimation.

Table 1: Water samples of different location before and after distillation.

S. No.	Sample of water		Location
	Before distillation	After distillation	
1.	Sample B1	Sample A1	Dr. PDKV Akola
2.	Sample B2	Sample A2	Shivani
3.	Sample B3	Sample A3	MIDC
4.	Sample B4	Sample A4	Kumbhari village

Table 2: Major cations and anions in water

Cations	Anions
Calcium (Ca^{2+})	Bicarbonate (HCO_3^-), Carbonate (CO_3^{2-})
Magnesium (Mg^{2+})	Chloride (Cl^-)
Sodium (Na^+)	
Potassium (K^+)	

Table 3: Different methods and standard value for measuring water quality parameters

S. N.	Parameter	Standard value	
		BIS	WHO
1.	pH	6.5 to 8.5	6.5 to8.5
2.	EC, dS/m	0.75 – 2.25	0.50
3.	TDS (ppm)	500	500
4.	Calcium, meq/L	3.8	3.8
5.	Magnesium, meq/L	2.5	2.5
6.	Sodium, meq/L	4.4	4.4
7.	Potassium, meq/L	0.3	0.26
8.	Chloride, meq/L	4.16	5.2

Results and Discussion

The double basin solar still integrated with vacuum tubes was designed and system was installed at the Department of Unconventional Energy Sources and Electrical Engineering, Dr. PDKV Akola.

Performance evaluation of double basin solar still integrated with vacuum tubes

Performance of solar still is generally expressed as the quantity of water produced by basin area. The quantity of water produced by solar still varies with solar radiation available, humidity, ambient temperature, sky condition and wind speed. The design parameters such as orientation of still, area of absorber, inclination of glass cover, slopes of cover, insulation material, depth of water, temperature of water and the temperature difference between glass cover and basin water affect the production rate [8]. The main parameter that affects the solar still performance is the mass of basin water in each effect. Hence, the performance of the system was evaluated at full load condition for winter and summer season at 3 cm depth of water. Four different water samples from different locations were taken to study the impact of salinity of water on the performance of system [9]. Temperature of water and temperature of condensing glass cover surface of lower basin, temperature of water and temperature of condensing glass cover surface of upper basin, temperature of outer glass cover were recorded with the help of calibrated thermocouples in combination with digital temperature indicator. The results obtained from experiments are summarized as follows:

Effect of water depth and temperature during winter

The effect of water depth and temperature in the system has been studied for the various depth of level. The water depth during the experimentation was considered and kept from 3 cm at upper and lower basin. The harnessing of solar radiation in the form of capturing the temperature by the water at upper and lower basin resulted in the output as distilled water [10]. The experiments were conducted during winter season *i.e.* January and February month. The output capacity of the system has been varied in both season as the effect of depth of water in basin and temperature [11]. The temperature at various stages of basin, solar radiation and the hourly output of distilled water has been recorded to study the characteristics of the system. The experimental recorded data of winter season for the month of January and February for the four samples and water depth of 3 cm has been analyzed and same has been presented.

Effect of water depth (3 cm) and temperature on yield

System configuration and integration of the main basin with the evacuated tube has greatly effect on the system performance and the yield. It has been observed that as intensity of solar radiation increased the temperature was also increased an it was found to be maximum of about 34.2 °C with corresponding solar radiation 629.75 W/m² at 14 h. It was also observed that the temperature at various locations inside the still depends on the climatic parameters i.e. solar radiation and ambient temperature (Table 4).

During the period from 9.00 h to 15.00 h, the temperature of entire system continuously increased due to exposure to solar radiation. However, in the late afternoon, the temperature of the system started to decrease but the decrease was not very significant due to trapped Infra Red radiation as the solar still act as greenhouse. Basin water temperature was 38 °C in the morning and increased to 80.6 °C during afternoon in lower basin integrated to vacuum tubes and maximum temperature achieved in upper basin was 77.7 °C and glass temperature during same period was observed to be 72.40 and 69.9 °C for lower and upper basin (table 4). Similar observation for sample 3 and 4 depicted in table 5 and 6.

Water analysis

Chemical analysis of impure and pure water which were used for study was carried out for pH, EC, TDS,Mg^{2+}, Ca^{2+}, Na^{+} ions etc. The data obtained during the experimentation is presented in table 7. It was observed from the table, the chemical analysis of pure (distilled) and impure (saline or tap) water has shown reduction in the pH, EC and various cations like Mg^{2+}, Ca^{2+}, Na+, and anions Cl-, carbonate, bicarbonate etc. in the pure water.

Table 7: Chemical properties of water before and after distillation.

S. N.	parameter	Before distillation				After distillation			
		B1	B2	B3	B4	A1	A2	A3	A4
1	pH	7.02	7.03	7.31	7.23	7.01	6.54	6.67	6.76
2	EC	1.50	1.26	1.40	1.60	0.01	0.01	0.01	0.01
3	Na^{++}	25.40	26.50	24.43	65.46	00	00	00	00
4	TDS	960	806.4	953.60	1024	6.4	6.4	6.4	6.4
5	Ca + Mg	22.00	34.50	31.60	28.0	3.6	5	4	2
6	Cl-	24.00	36.00	40.00	22.00	2	3.5	2.2	5.7
7	HCO_3	5.22	5.68	6.52	4.66	0.03	0.03	0.12	0.12

The data presented indicated the values obtained for cations and anions during the course of investigation. Based on the data it was observed that the considerable amount of contains Ca +Mg was found in the range of 22 to 34.50 $meqL^{-1}$ before distillation while it was reduced to 2 $meqL^{-1}$after distillation, which was followed by sodium 24.43 to 65.46 before distillation and 0 $meqL^{-1}$after distillation. Similarly, in respect of anions it was observed that bicarbonate was found to be in between 4.66 to 6.52 $meqL^{-1}$before distillation and 0.03 to 0.12 $meqL^{-1}$ after distillation. The chloride was 22 to 40 $meqL^{-1}$ and 2 to 5.7 $meqL^{-1}$ before and after distillation respectively.

In case of total dissolved solid, it was reduced to 6.4 after distillation which was in the range of 953 to 1024 ppm for before distillation. The electric conductivity of impure water sample was found in the range of 1.50 to 1.60 dSm^{-1}which was reduced remarkably to 0.01 dSm^{-1}showing the significance of adopted methodology for getting good quality distilled water.

Conclusions

The study revealed that, the present design increased the distillate yield due to integration of double basin solar still with vacuum tubes. The daily yield obtained was 11 liters in winter at 3 cm basin water depth. The yield decreases further with increase in water depth and as salinity of water increased. The chemical analysis of distilled water indicated that the water can be used in laboratories and battery.

Table 4: Average variations in ambient conditions, temperatures at various locations in solar still and distillate yield with respect to time of sample I at 3 cm water depth during winter

Time (h)	Solar radiation (W/m^2)	Ambient temperature (°C)	Relative humidity (per cent)	Wind speed (m/s)	T_e (°C)	T_{w1} (°C)	T_{g1} (°C)	T_{w2} (°C)	T_{g2} (°C)	T_{go} (°C)	Yield (mL)
8:00	100.85	27.9	37.50	2.00	36.7	38.0	34.1	37.0	33.6	30.4	30
9:00	177.70	29.0	37.50	2.05	42.1	44.1	38.8	42.3	37.4	34.5	105
10:00	284.80	29.6	34.50	1.60	50.1	52.8	46.7	51.7	46.1	42.1	340
11:00	478.60	30.5	30.00	1.95	59.7	61.5	54.4	59.2	52.6	48.7	505
12:00	684.85	32.0	26.50	2.40	69.1	72.6	65.0	70.9	63.8	59.5	760
13:00	690.50	33.2	26.50	2.20	75.7	77.9	69.7	75.1	67.3	63.0	980
14:00	629.75	34.2	26.00	1.70	80.5	80.6	72.4	77.7	69.9	67.3	1365

15:00	512.30	32.9	28.50	1.60	78.1	78.3	70.8	75.7	68.5	66.0	1430
16:00	396.80	31.8	32.00	1.90	76.4	76.3	70.0	74.3	68.3	64.7	1390
17:00	213.00	31.0	34.50	1.60	75.3	73.2	69.2	71.5	67.9	63.9	1290
18:00	102.70	29.7	33.50	1.45	74.4	71.5	69.1	69.7	67.6	62.7	1220
Avg.	388.35	31.1	31.55	1.86	65.3	66.1	60.0	64.1	58.4	54.8	11662

Table 5: Average variations in ambient conditions, temperatures at various locations in solar still and distillate yield with respect to time of sample II at 3 cm water depth during winter.

Time (h)	Solar radiation (W/m^2)	Ambient temperature (°C)	Relative humidity (per cent)	Wind speed (m/s)	T_e (°C)	T_{w1} (°C)	T_{g1} (°C)	T_{w2} (°C)	T_{g2} (°C)	T_{go} (°C)	Yield (mL)
8:00	101.55	27.4	34.00	1.30	37.0	39.1	35.1	37.7	34.1	30.2	40
9:00	177.90	28.4	33.51	1.30	42.4	44.3	39.2	42.9	38.0	34.2	110
10:00	279.65	29.4	32.55	1.50	52.2	54.1	48.1	52.0	46.4	43.1	235
11:00	494.35	30.9	28.61	1.85	58.1	62.0	54.8	59.7	53.1	50.8	445
12:00	656.15	32.6	28.50	2.15	71.5	73.5	65.6	70.7	63.3	60.3	615
13:00	673.30	33.1	27.02	1.70	75.8	79.1	70.9	76.2	68.6	64.8	1050
14:00	654.40	33.9	27.02	1.75	80.5	82.0	73.6	79.9	72.1	68.6	1390
15:00	539.00	32.2	27.51	1.55	78.3	79.9	72.5	77.7	70.8	66.8	1515
16:00	382.55	31.1	30.02	1.90	76.4	77.8	71.9	75.5	69.9	66.4	1490
17:00	225.05	30.1	33.01	2.00	75.7	74.9	70.8	73.4	69.5	66.7	1375
18:00	94.60	29.4	35.00	1.85	74.9	72.7	70.3	71.0	69.0	65.3	1335
Avg.	388.95	30.8	30.61	1.71	65.7	67.2	61.1	65.1	59.5	56.1	11900

Table 6: Average variations in ambient conditions, temperatures at various locations in solar still and distillate yield with respect to time of sample III at 3 cm water depth during winter

Time (h)	Solar radiation (W/m^2)	Ambient temperature (°C)	Relative humidity (per cent)	Wind speed (m/s)	T_e (°C)	T_{w1} (°C)	T_{g1} (°C)	T_{w2} (°C)	T_{g2} (°C)	T_{go} (°C)	Yield (mL)
8:00	100.85	27.3	36.00	1.45	36.3	38.5	34.3	37.2	33.4	30.0	30
9:00	188.75	28.3	40.50	1.60	42.7	45.0	39.5	42.4	37.4	34.2	85
10:00	289.70	29.1	33.50	1.95	48.4	54.5	48.1	51.7	45.9	42.7	185
11:00	432.20	30.2	29.00	1.85	54.1	60.6	51.5	56.1	49.9	46.6	390
12:00	671.15	31.8	28.00	1.85	66.6	71.5	63.6	68.3	60.9	56.2	550
13:00	655.10	32.9	25.00	1.60	76.5	79.4	71.2	76.2	68.6	64.8	1005
14:00	636.30	34.7	23.00	1.45	79.5	81.0	72.7	78.9	71.0	68.7	1290
15:00	543.35	33.3	27.00	1.80	77.2	78.6	71.2	76.5	69.5	66.4	1430
16:00	421.10	31.8	31.00	1.45	76.3	77.1	70.7	75.3	69.2	65.0	1440
17:00	244.90	30.7	35.00	2.25	74.7	74.7	70.1	73.0	68.5	63.7	1320
18:00	94.00	29.9	36.00	2.20	72.8	69.7	67.2	69.4	67.2	62.5	1280
Avg.	388.85	30.9	31.27	1.77	64.1	66.4	60.0	64.1	58.3	54.6	11150

Table 7: Average variations in ambient conditions, temperatures at various locations in solar still and distillate yield with respect to time of sample IV at 3 cm water depth during winter.

Time (h)	Solar radiation (W/m^2)	Ambient temperature (°C)	Relative humidity (per cent)	Wind speed (m/s)	T_e (°C)	T_{w1} (°C)	T_{g1} (°C)	T_{w2} (°C)	T_{g2} (°C)	T_{go} (°C)	Yield (mL)
8:00	105.15	27.5	34.50	1.65	37.2	39.0	34.8	37.9	34.1	31.0	40
9:00	184.30	28.7	35.00	1.80	42.5	44.1	38.6	42.2	37.2	33.7	115
10:00	304.05	29.6	33.50	1.60	50.6	53.0	46.7	50.7	45.0	40.3	245
11:00	497.25	31.6	28.00	1.60	56.5	61.6	54.5	58.4	51.9	47.7	455
12:00	667.15	32.9	25.00	1.65	69.4	71.5	63.7	69.7	62.5	59.1	610
13:00	671.05	34.1	24.50	1.85	75.9	77.9	69.8	75.7	68.2	64.2	1040
14:00	636.55	35.0	22.00	1.75	79.6	81.1	73.0	78.4	70.6	66.2	1380
15:00	539.85	33.5	24.50	2.10	77.2	78.4	71.2	76.8	70.0	65.8	1520
16:00	408.60	32.2	29.50	1.90	75.6	76.7	70.3	75.5	69.3	65.2	1470
17:00	251.50	31.4	34.00	1.75	74.9	74.2	69.7	72.8	68.6	64.4	1380
18:00	100.80	30.7	34.00	1.80	74.2	72.0	69.5	70.1	68.2	63.7	1335
Avg.	396.93	31.5	29.50	1.77	64.9	66.3	60.1	64.4	58.7	54.6	11790

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