Performance Evaluation of A Solar Still Coupled to an Evacuated Tube Collector type Solar Water Heater

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Abstract - Solar distillation is a promising method for the supply of freshwater to rural communities. Worldwide passive solar still is used for solar distillation plants due to its simplicity in construction and operation, low cost and however the yield is low. Various active methods have been developed to overcome this issue. These developments create additional costs for the system. The main objective of this project is to effectively utilize the solar water heater for solar still productivity enhancement, which works as a hybrid system. The evacuated tube collector model solar water heater was coupled to a solar still, and the performance study was conducted at various timings with different operating conditions like Solar still operated alone and Hybrid Still operated during daytime with various water depths and various water samples. Both Theoretical and Experimental analysis were conducted and the results were compared. The water quality results for different water samples for both untreated and treated water were tabulated.

Keywords: Evacuated tube collector, Productivity, Solar still, Solar water heater, Water quality

I. INTRODUCTION

Today fresh water demand is increasing continuously, because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. Only about 3 % of the world water is potable and this amount is not evenly distributed on the earth Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. Lack of fresh water is a prime factor in inhibiting regional economic development. Seawater and sometimes brackish water desalination constitute an important option for satisfying current and future demands for fresh water in arid regions.Desalination can be achieved by using a number of techniques.The conventional distillation process namely reverse osmosis, electro dialysis, multieffect evaporation etc are not only energy intensive but also uneconomical when the demand for the fresh water is small

Solar distillation is an attractive Saline water Distillation. The basin type of solar still is simple in design, manufacture and operation. In addition this process is cost free. Enhancing stills yield have been studied by many investigators and they have suggested many approaches like concave wick, tube type, and weir type was also reported for productivity enhancement. Also approaches like using different insulating materials, brine level, double slope concentrators, etc.

II. PROPOSED SYSTEM

T. V. Ramachandra [13] proposed a solar energy potential assessment using GIS.He proposed that Renewable energy systems use resources that are constantly replaced in nature and are usually less polluting. The potential analysis reveals that, maximum global solar radiation is in districts such as Uttara Kannada and Dakshina Kannada. Global solar radiation in Uttara Kannada during summer, monsoon and winter are 6.31, 4.40 and 5.48 kWh/sq.m, respectively. Similarly, Dakshina Kannada has 6.16, 3.89 and 5.21 kWh/sq.m during summer, monsoon and winterSantosh M. Avvannavar,Monto Mani1, Nanda Kumar [14] conducted a research on Improving access to safe drinking water can result in multi-dimensional impacts on people's livelihood. They concluded that solar still is the safe and suitable way for water desalination. Hitesh N Panchal [22] worked on the effect of various parameters on

productivity of Single slope and double slope solar still. Distilled output of double slope solar still is higher compared with single slope. Distilled output from the solar still is higher at 13:00. Solar insolation is highest at13:00. By use of sprinkler and increased condensation area, the distilled output is increased up to 20%. By use of 2.0 cm water depth, proper utilization of the solar insolation as well as distilled output is increased. So permissible water depth is 2.0 cm and it should be maintained constant by constant head tank. O.O.Badran, H.A .Al –Tahaineh [10] performed a study on the Effect of coupling a Flat plate collector on the solar still productivity. He carried out experiment for different parameters to enhance the productivity and the same were studied.Single slope Solar still with mirrors fixed to the interior sides of the still was coupled to an FPC.It was found that coupling effect has increased the productivity by 36% compared to that of an active solar still K.Voropolous, E.Mathioulakis, V.Belessiotis [7] conducted an Experimental Investigation of the behavior of solar still coupled with hot water storage tank. G.N.Tiwari, J.N.Thomas and Emran Khan [4] studied on thermal analysis of solar distillation to optimize the inclination of the glass cover for maximum yield.Enhancing stills yield have been studied many investigators and they have suggested many approaches like concave wick, tube type, and weir type was also reported for productivity enhancement. Also approaches like using different insulating materials, brine level, double slope concentrators, etc.The single basin solar still was coupled with a flat plate collector (FPC) in natural circulation mode, which resulted in a productivity enhancement of 30 to 52% compared to the simple solar still. Over 50% of the productivity enhancement was achieved by coupling the solar still with a flat plate solar collector in forced circulation mode. The solar still coupled with a parabolic concentrator increased the productivity by 35 to 45%, and this increase was larger in the double effect still. The solar water heater is the best option for increasing the basin water temperature. The evacuated tube collector (ETC)-type solar water heater is more advantageous than the flat plate collector type due to its greater reduction in heat losses caused by the vacuum present in the tubes. Evacuated tube solar collectors have improved performance compared to the flat plate collectors, particularly for high temperature operations

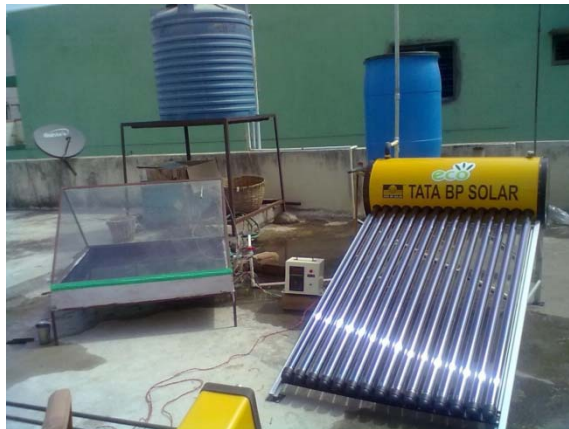## III. EXPERIMENTAL SETUP AND RESULTS

Fig .1.Experimental Set up

A double slope single basin solar still coupled with an ETC solar water heater is designed and constructed for the experimental work. It is as shown in the figure 1 .The basin of the solar still is square in shape with an absorber area of 1m2. The basin structure of the solar still is composed of a galvanized iron sheet. The inner side of the basin is painted black to maximize the absorption of solar radiation. The bottom and sides of the still basin were well insulated with a Glass wool layer that was 0.025 m thick. The box surrounding the still basin is made of plywood. An inlet pipe was fixed to the rear side of the solar still to supply brackish water. One additional pipe was fixed at the left side of the solar still to drain out the dirty water after the distillation is finished. An ordinary clear window with a glass thickness of 0.005 m was used as the top cover of the solar still and inclined at an angle of 45°. The total experimental setup was arranged to face in the southern-northern direction to receive the maximum solar radiation. A silicon rubber sealant was used as the seal between the glass cover and body of the solar still to prevent leakage at the stem. The distillate water condensed from the glass cover was collected in a distillation trough fit on the lower side of the solar still. Additionally, a rubber pipe was connected to the collection tray to collect desalinated water into a measuring jar. Holes were drilled in the body of the still to attach the thermocouples that measured the temperature at various locations. The hybrid solar still unit was operated in the month of April – May 2012 under

local conditions.The above designed single basin solar still was coupled to an ETC-type solar water heater that was manufactured by TATA BP SOLAR, which is an approved manufacture of ETC-type solar water heaters by the Ministry of New and Renewable Energy Sources (MNRE), Government of India.
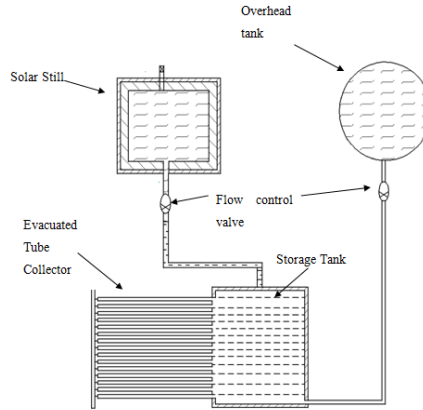
Working Principle

Fig 2: Schematic Diagram of the Experimental Set up

Initially, the tap water was supplied to the ETC solar water heater and run for a day to reach a steady state condition. The quantity of water in the basin of the solar stills was maintained at 10 kg for both passive and active modes of operation. The experiment commenced two days after assembly of the glass cover and after reaching steady state conditions in the storage tank.The experimental performance tests were conducted from April to July 2012. To find the effect of coupling an ETC solar water heater with the solar still, Different tests explained below were performed:

- Solar Still Alone

- Hybrid Still (Solar Still + ETC type Solar Heater) operated from 8AM till 5PM

These experiments were conducted for different Water samples (River water, Borewell water and Synthetic water (KMnO4)

I. **THEORETICAL ANALYSIS:** Design Parameters for Theoretical Analysis:

Table 1: Various Parameters for Theoretical analysis

Parameter	Value	Unit
A_s	1	m^2
C_w	4190	J/kg°C
M_w	10	Kg
T	3600	S
α_w'	0.34	
α_g'	0.05	
α_b'	0.38	
L_g	0.005	M
K_g	0.78	W/m°C
L_i	0.025	M
K_i	0.08	W/m°C
V	0–6	m/s
Σ	$5.67 \times 10{-8}$	W/m^2K^4
ε_{eff}	0.82	

A_L	3.32	m^2
A_{ET}	1.0575	m^2
F_R	0.831	
$(\alpha\tau)_c$	0.8	
U_{LC}	0.81	W/m^2°C

1. **The outer surface of the glass cover:**

$$T_{go} = \frac{\frac{K_g}{L_g}T_{gi} + h_{t,g-a}T_a}{h_{t,g-a} + \frac{K_g}{L_g}} \quad \dots\dots\dots\dots (1)$$

Total heat transfer coefficient from the glass cover to ambient is given by,

$$h_{t,g-a} = 5.7 + (3.8 * V) \dots\dots\dots (6.2)$$

2. The inner surface of the glass cover.

$$T_{gi} = \frac{\alpha'_g * I(t)_s + h_{t,w-g}T_w + U_{c,g-a}T_a}{h_{t,w-g} + U_{c,g-a}} \quad \dots (6.3)$$

Where, $$U_{c,g-a} = \frac{\frac{K_g}{L_g}h_{t,g-a}}{\frac{K_g}{L_g}+h_{t,g-a}} \quad \dots (6.4)$$

The total heat transfer coefficient between water and glass is given by,

$$h_{t,w-g} = h_{c,w-g} + h_{e,w-g} + h_{r,w-g} \quad \dots (6.5)$$

The radiative heat transfer coefficient between water and glass is given by,

$$h_{r,w-g} = \varepsilon_{eff}\,\sigma\,[(T_w + 273)^2 + (T_{gi} + 273)^2] \times (T_w + T_{gi} + 546)] \quad \dots (6)$$

The convective heat transfer coefficient between water and glass is given by,

$$h_{c,w-g} = 0:884*(\Delta T')^{1/3} \quad \dots\dots\dots (7)$$

Where, $\Delta T^1 = (T_w - T_{gi}) + [(P_w - P_{gi}) \times (T_w + 273) / (268.9 \times 10^{-3} - P_w)]\dots\dots\dots\dots(6.8)$

$$p_w = e^{[25.317 - (\frac{5144}{274+T_w})]} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

$$p_{gi} = e^{[25.317 - (\frac{5144}{274+T_{gi}})]} \quad \dots\dots\dots\dots\dots\dots\dots\dots (10)$$

The evapourative heat transfer coefficient between water and glass is given by,

$$h_{e,w-g} = 16.273 \times 10^{-3} \times h_{c,w-g} \times \frac{(p_w - p_{gi})}{(T_w - T_{gi})} \quad (11)$$

The total heat transfer coefficient between water and glass is given by,

$$h_{t,w-g} = h_{c,w-g} + h_{e,w-g} + h_{r,w-g}$$

The inner surface of the glass cover:

$$T_{gi} = \frac{\alpha'_g * I(t)_s + h_{t,w-g}T_w + U_{c,g-a}T_a}{h_{t,w-g} + U_{c,g-a}}$$

3.The basin liner :

$$T_b = \frac{\alpha'_{-b}I(t)_s + h_w T_w + h_b T_a}{h_w + h_b} \quad \dots\dots (12)$$

Where, $\quad \alpha'_{-b} = \alpha_{-b}(1 - \alpha'_g)(1 - \alpha'_w)$

The overall heat transfer coefficient from the basin liner to ambient is given by,

$$h_b = \left[\frac{L_i}{K_i} + \frac{1}{h_{t,b-a}}\right]^{-1} \quad \dots\dots (13)$$

Since there is no velocity in the bottom of the still , $\qquad\qquad h_{t,b-a} = h_{t,g-a}$

The convective heat transfer co-efficient between basin to water is given by,

$$h_w - \frac{K_w}{X_w} C (Gr * Pr)^n \dots\dots\dots (14)$$

$$Gr = \frac{g\beta X_w^3 \rho_v^2 \Delta T'}{\mu_v^2} \qquad Pr = \frac{\mu_v C_p}{K_v}$$

The overall bottom heat loss coefficient is given by,

$$U_b = \frac{h_w h_b}{(h_w + h_b)} \dots\dots\dots\dots\dots\dots\dots (15)$$

The overall top heat loss coefficient from the water to the ambient is given by,

$$U_t = \frac{h_{t,w-g}h_{t,g-a}}{(h_{t,g-a} + U_{wg})} \dots\dots\dots\dots\dots\dots (16)$$

Where, $\quad U_{wg} = \dfrac{h_{t,w-g}\frac{K_g}{L_g}}{(h_{t,w-g} + \frac{K_g}{L_g})} \dots\dots\dots\dots (17)$

The basin liner:

$$T_b = \frac{\alpha'_{-b}I(t)_s + h_w T_w + h_b T_a}{h_w + h_b}$$

4. The water mass:

$$T_w = \frac{\overline{f(t)}}{a}[1 - e^{-at}] + T_{wo}e^{-at} \dots\dots\dots (18)$$

Where, $a = \left[\dfrac{U_{eff}}{(MC)_w}\right] \qquad f(t) = \left[\dfrac{I_{eff} + U_{eff}T_a}{(MC)_w}\right]$

$$I_{eff} = F_R(\alpha\tau)_c I(t)_c + (\alpha\tau)_{eff}I(t)_s$$

$$U_{eff} = U_{LS} + F_R U_{LC}$$

Assuming $F_R = 0.81, \; U_{LC} = 0.86$

$$U_{LS} = U_t + U_b \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

$$(\alpha\tau)_{eff} = \left[\alpha'_b \frac{h_w}{(h_w + h_b)} + \alpha'_w + \alpha'_g \frac{h_{t.w-g}}{(h_{t.g-a} + U_{wa})} \right] \ldots\ldots\ldots (20)$$

$$I_{eff} = F_R (\alpha\tau)_c I(t)_c + (\alpha\tau)_{eff} I(t)_s$$

Hence the water temperature is calculated as ,

$$T_w = \frac{\overline{I(L)}}{a} [1 - e^{-at}] + T_{wo} e^{-at} \ldots\ldots\ldots\ldots (21)$$

The hourly yield is given by,

$$m_{ew} = \frac{h_{e,w-g}(T_w - T_{gi}) \times 3600 \times A_s}{L} \ldots\ldots (22)$$

Theoretical calculations were done for water depths of 1.5cm and 2cm and for various operating conditions for hybrid still operated from 8AM till 5PM.Also the calculations were done for different water samples and the same has been tabulated below.

Table 2: Tabulation of Theoretical amount of water collected

Operation	Still Alone			Hybrid Still operated from 8AM to 5PM		
Water Depth	1	1.5	2	1	1.5	2
River water	2.69	2.37	2.27	4.43	4.24	3.84
Borewell water	2.47	2.22	2.20	4.33	4.22	3.67
River water + kmno4	2.98	2.49	2.41	4.58	3.72	3.91

Experiments were conducted to understand the performance of the solar still coupled with the solar water heater for comparison with the passive solar still alone. As can be seen from the hourly yield equation, the water temperature and the inner glass cover temperature were the most influential parameters on the yield calculation.
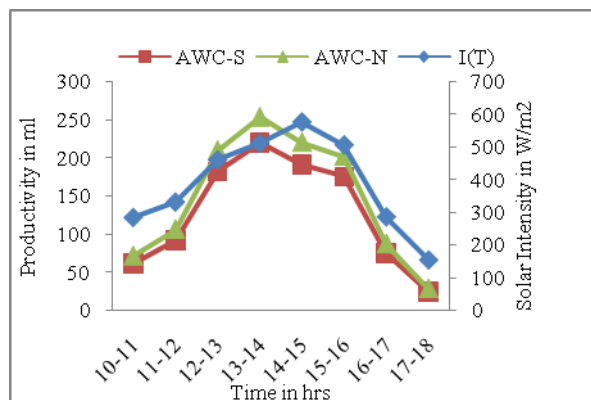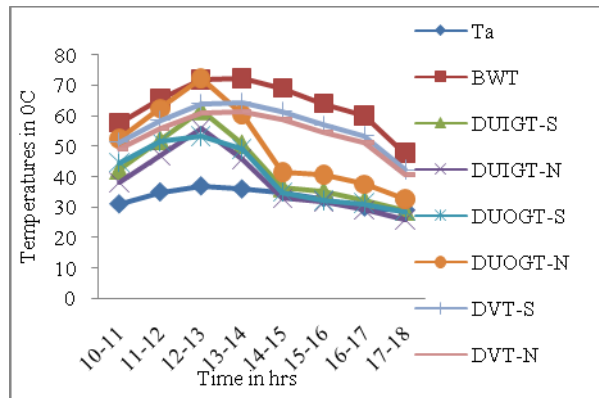
Graph .1: Hourly variation of Productivity and Solar Intensity for a Solar Still Alone with 1cm water depth for River Water
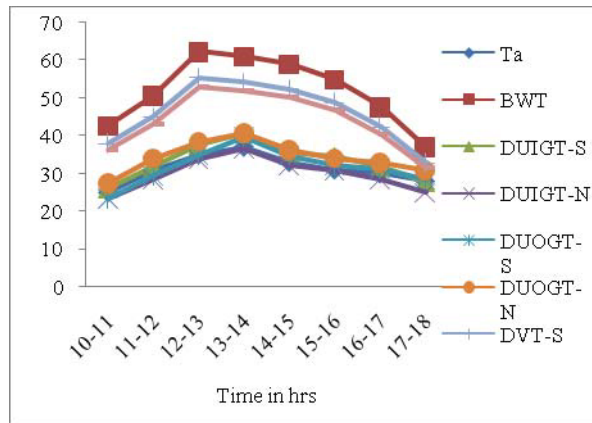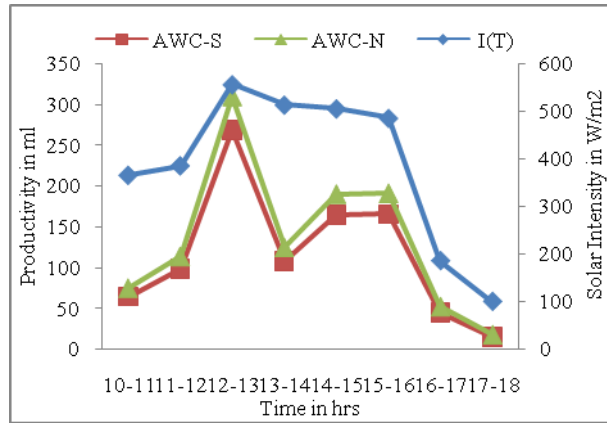

Graph 2: Hourly variation of various Temperatures for a Solar Still Alone with 1cm water depth for River Water
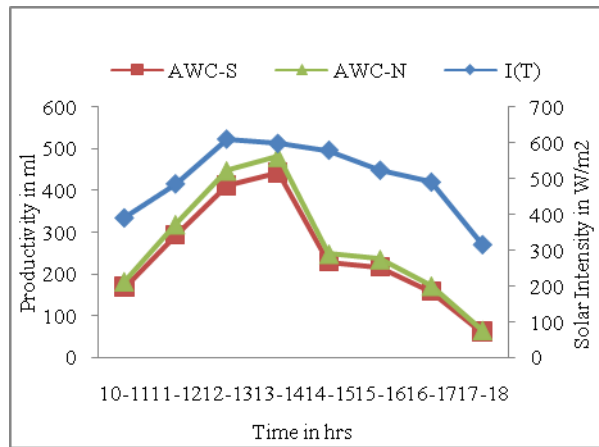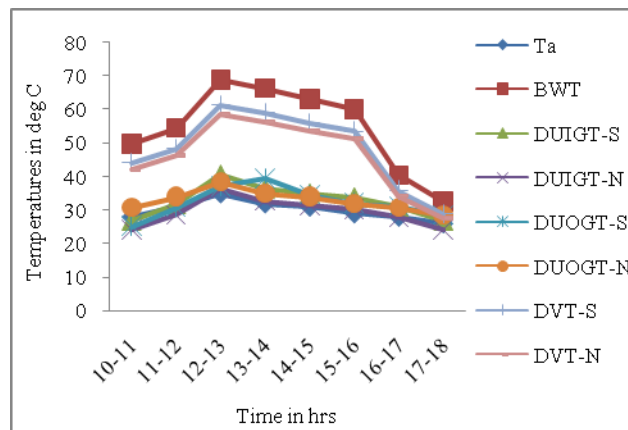

Graph 3: Hourly variation of Productivity and Solar Intensity for an Hybrid still with 1cm water depth for River water
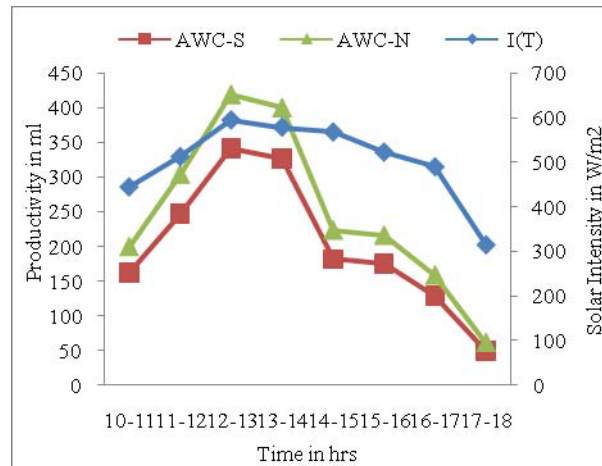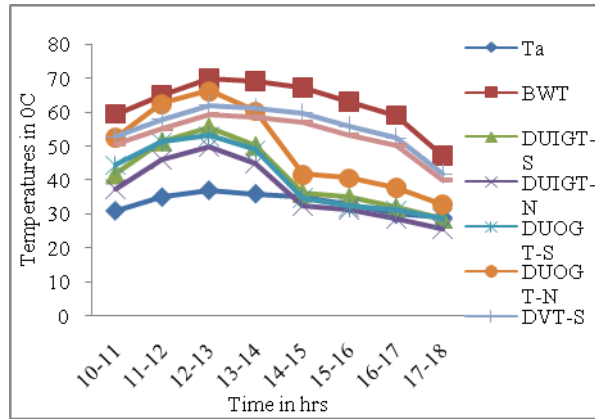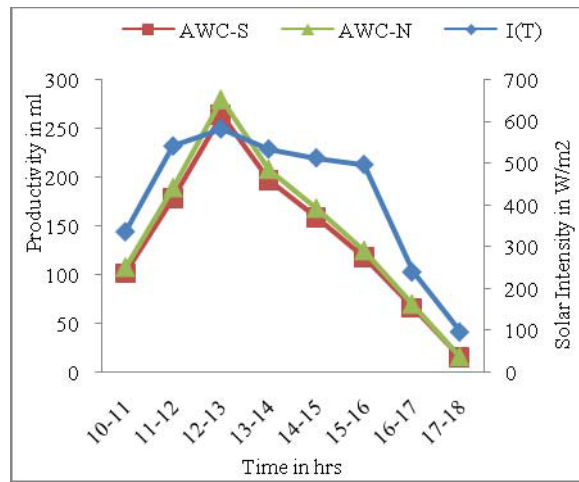

Graph 4: Hourly variation of various temperatures for an Hybrid still with 1cm water depth for River water

Graph 5: Hourly variation of Productivity and Solar Intensity for a Solar Still Alone with 1cm water depth for Borewell Water

Graph 6: Hourly variation of various Temperatures for a Solar Still Alone with 1cm water depth for Borewell Water
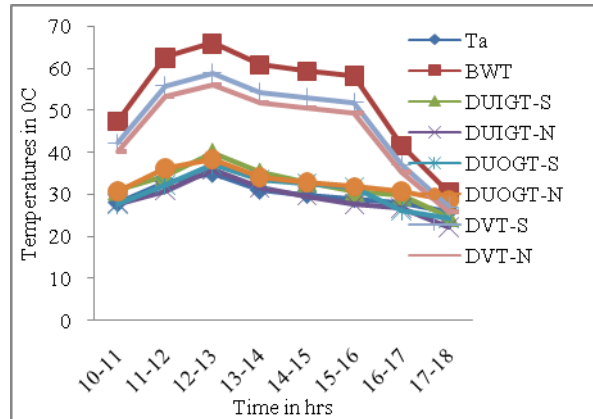

Graph 7: Hourly variation of Productivity and Solar Intensity for an Hybrid still with 1cm water depth for Borewell water
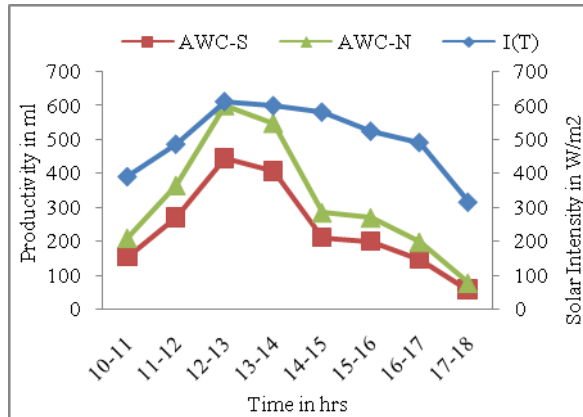
Graph 8: Hourly variation of various temperatures for an Hybrid still with 1cm water depth for Borewell water
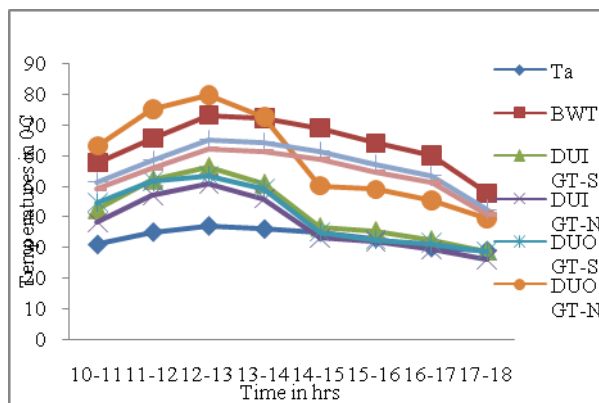

Graph 9: Hourly variation of Productivity and Solar Intensity for a Still Alone with 1cm water depth for River Water $+ KMnO_4$

Graph 10: Hourly variation of various Temperatures for a Still Alone with 1cm water depth for River Water $+ KMnO_4$

Graph 11: Hourly variation of Productivity and Solar Intensity for an Hybrid still with 1cm water depth for River water + KMnO$_4$

Graph 12: Hourly variation of various temperatures for an Hybrid still with 1cm water depth for River water + KMnO$_4$

Experimental results shows that Solar Still coupled with an Evacuated tube collector type of solar heater increases the solar still productivity by 46.91% when the hybrid still was operated from 8AM till 5PM compared to still alone.
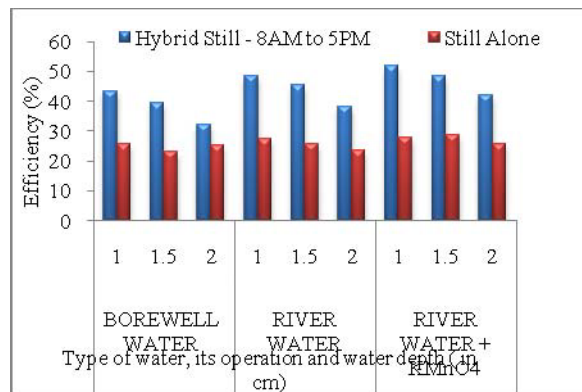

Graph 13: Comparision of Efficiency for various conditions
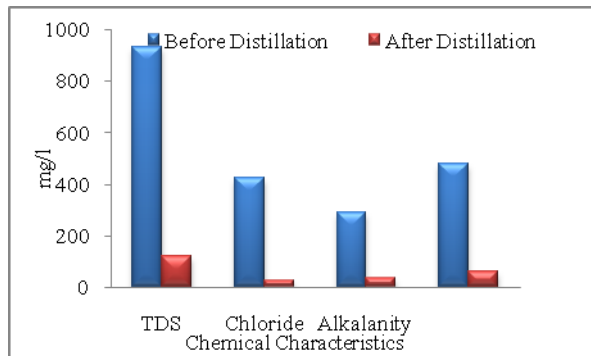
7.3 Water Analysis:

To determine the purity of distilled water collected from the solar distillation unit. The following tests have been carried for the water entering and leaving the distillation unit. The summarized test reports for distilled and non-distilled water are shown in the bar charts.
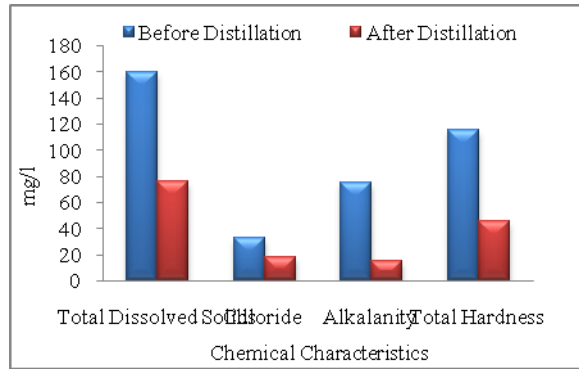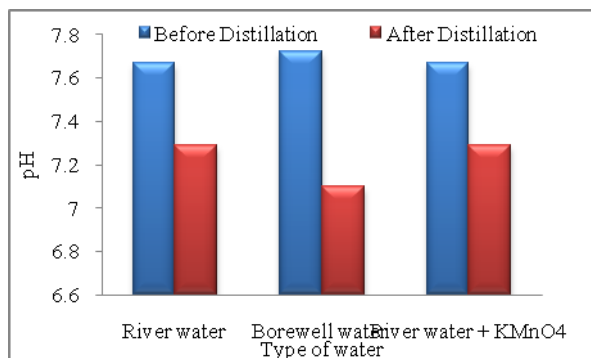
Graph 14: Water analysis chart for River Water
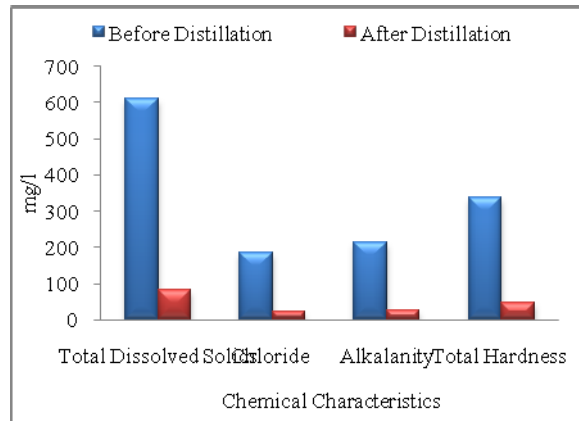
Graph 15: Water analysis chart for Borewell Water

Graph 16: Water analysis chart for River Water + KMnO$_4$

Graph 17: pH Variations for various water samples

Water taken for the experimental purpose were tested before and after the distillation Water.The variations of various chemical characteristics of the water before and after the treatment are plotted in the graph for river water. Also for borewell water and river water + KMnO$_4$, the variations are plotted in graph pH variation for various water samples are plotted in graph.

IV.CONCLUSIONS

An experimental investigation is done for comparing a passive solar still and an ETC solar water heater coupled with a solar still.

- Productivity of Solar Still increases from 39 to 59% with hybrid unit.i.e when a Solar Still is coupled to an ETC type of solar water heater and operated from 8AM to 5PM
- The efficiency for 1cm water depth ranged from 43 to 52%, for 1.5cm it ranged from 39 to 48% and for 2cm it ranged from 32 to 41% for a Hybrid Solar Still operated during day time. Hence it can be concluded that the efficiency of the still decreases with the increase in water depth
- The thermal efficiency of active solar still is higher than the passive solar still. It ranges from 32 to 48% for hybrid unit operated during the day.
- Adding the dissolved salt like KMnO$_4$ to river water increased the efficiency from 46.91 to 48.83% for a water depth of 1cm.
- The theoretical analysis was in good agreement with the experimental results.
  Solar energy is the best alternative heating energy source. It is renewable and easily available in all parts of the world which is cheap and clean. The hybrid solar still tested confirms the high quality drinking water from the source water of very poor quality. Finally, it can be concluded that use of solar distillation promises to enhance the quality of life and to improve health standards in remote areas also.

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