International Journal of Research
ISSN: 2348-6848 Vol-3, Special Issue-19
Special Issue on
National Workshop on Emerging Sector of Engineering and Management (NWESEM-2016)

Experimental Analysis and Optimization of Solar Water Distillation System

Tonish Kumar Mandraha[1]; Bhupendra Gupta[2]; Ankur Vishwakarma[3]& Yashwant Kumar Vishwakarma[4]

[1]LNCT, Jabalpur, Department of Mechanical
[2]Jabalpur Engineering College, Jabalpur Department of Mechanical
[3]GGCT, Jabalpur Department of Mechanical
[4]SAIT, Jabalpur Department of Mechanical, India
mandrahatonish@gmail.com

Abstract

Present paper is an investigation in variation of water yield in single slope solar water still system attached with additional solar collector. This work has been carried out in a clear sky day in month of Feb, 2016. The optimization of water output is carried out for three distinct water levels (0.06, 0.12, 0.18 m).The inclination angle for both the devices are 23^0, facing south for atmospheric conditions of Jabalpur (M.P.). Daily observations were taken for different conditions. Temperature, relative humidity, wind velocity and water distillate have been recorded. The quality of water output has also been tested in laboratory to confirm its drinking abilities. Experiment investigation shows maximum efficiency of solar still for water level of 0.06 m compare to other two levels i.e., 0.12 & 0.18 m.

Keywords: solar water still, solar energy, passive techniques, thermal efficiency, water quality.

1. Introduction

Drinking water or fresh water is important substance in today's climate. It is absolutely essential for life. The freshwater availability is becoming scarce with time, leading to severe water crisis in many parts of the world. This is attributed mainly to uneven distribution of water resources and steep rise in population from rural to the urban areas.

Solar water distillation system is a highly promising and an environment friendly technology. In India, solar stills are used for the domestic purposes. They are generally used to meet small-scale demands. This process removes impurities, such as salts and heavy metals, and eliminates microbiological organisms. In this system, water is first evaporated by absorbing solar energy followed by its condensation, to produce pure water. The condensate is than drain out using an outlet channel. Pre-heating of water is done by the use of additional solar collector to the main system. This results in improvement in solar still performance and increased water distillate. The performance of solar distillation depends upon the design of solar still and climatic conditions.

2. Principle and Heat Transfer Mode

The basic principle of solar water still is simple, yet effective, as distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water

International Journal of Research
ISSN: 2348-6848 Vol-3, Special Issue-19
Special Issue on
National Workshop on Emerging Sector of Engineering and Management (NWESEM-2016)

evaporates, water vapor rises, condensing on the glass surface for collection. This process removes impurities, such as salts and heavy metals, and eliminates microbiological organisms. The end result is water cleaner than the purest rainwater.

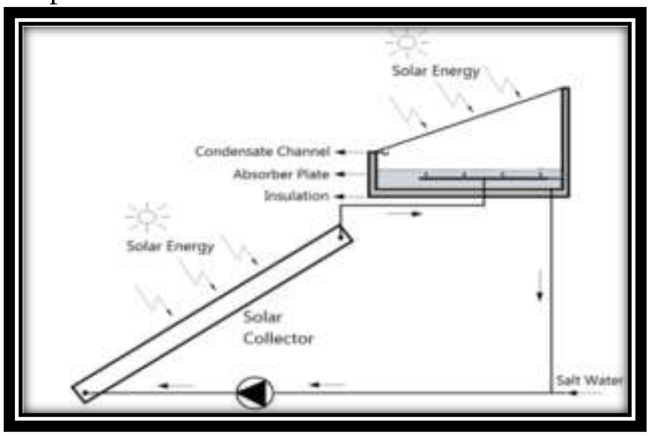

Figure 1: Showing distillation process in solar water still with collector

The heat transfer in solar still is mainly classified into two ways, internal and external heat transfer.

1) Internal heat transfer: In solar still basically internal heat is transferred by evaporation, convection and radiation. The convective and evaporative heat transfers takes place simultaneously and are independent of

(a) Radiative heat transfer,

(b) Convective heat transfer.

2) External heat transfer: The external heat transfer in solar still is mainly governed by conduction, convection and radiation processes, which are independent, each other.

a) Top loss heat transfer coefficient: The heat is lost from outer surface of the glass to atmosphere through convection and radiation modes. The glass and atmospheric temperatures are directly related to the performance of the solar still. So, top loss is to be considered for the performance analysis. The temperature of the glass cover is assumed to be uniform because of small thickness.

b) Side and bottom loss heat transfer coefficient: The heat is transferred from water in the basin to the atmosphere through insulation and subsequently by convection and radiation from the side and bottom surface of the basin.

3. Governing Equations

System governing equations are as follows:

$$Cp = 999.2 + 0.1434 \times T_v + 1.101 \times 10^{-4} \times Tv^2 - 6.7581 \times 10^{-8} \times Tv^3 \quad \ldots (1)$$

$$\rho = 353.44/(T_v \times 273.15) \quad \ldots (2)$$

$$k = 0.0244 \times 0.7673 \times 10^{-4} \times T_v \quad \ldots (3)$$

$$\mu = 10718 \times 10^{-5} + 4.620 \times 10^{-8} \times T_v \quad \ldots (4)$$

$$L = 3.1615 \times 10^{6} \times [1 - (7.616 \times 10^{-4} \times T_v)] \quad \ldots (5)$$

$P_{ci} = exp\,[25.317 - 5144/(T_{ci} + 273)$ .... (6)

$P_w = exp\,[25.317 - 5144/(T_w + 273)]$.. (7)

$\beta = 1/(T_v + 273.15)$ .... (8)

Thus the heat transfer per unit area per unit time evaporation from the water surface to glass covers

$q_{ew} = h_{ew}\,(T_w - T_{ci})$ .... (9)

The relation between evaporative heat transfer coefficient and convective heat transfer coefficient

$h_{ew} = 0.016273 \times h_{cw} \times (P_w - P_{ci} / T_w - T_{ci})$ .... (10)

$h_{ew} = 0.016273 \times [(k/a)^c (Gr.Pr)^n \times (P_w - P_{ci} / T_w - T_{ci})]$ .... (11)

$q_{ew} = 0.016273 \times [(k/a)^c (Gr.Pr)^n \times (P_w - P_{ci} / T_w - T_{ci}) \times (T_w - T_{ci})]$................................... (12)

The rate of mass transfer m_{ew} is given by

$m_e = q_{ew} / L$ .... (13)

$m_w = 0.016273(P_w - P_{ci})(k/a)^c (Gr.Pr)^n \times (3600/L) \times A_w$ .... (14)

Efficiency calculation

Thermal efficiency of solar still is

$\eta = [M_{ew} \times L / I \times A_g \times t] \times 100\%$ .... (15)

Overall Thermal efficiency of solar still when solar collector is attached

$\eta = \sum M_{ew}\, L / \sum [\{I(t)_c \times A_c \times 3600\} + \{I(t)_s \times A_s \times 3600\}] \times 100\%$ .... (16)

4. Experimental Setup and Methodology

The experimental setup of single slope solar still is shown in Figure 2(a). The specifications of the set-up are given in Table no. 1. It is an airtight basin. The top cover has transparent glass. The inner surface of the square base is blackened to efficiently absorb the solar radiation incident at the surface. Insulation is providing between outer surface of iron sheet and inner surface of wooden box. The brackish or saline water is feed into the basin for purification. The solar radiation that passes through the transparent plane glass heats water that starts evaporating. This evaporated water gets condensed on the underside of the glass, which is further collected using channel.

As shown in the Fig: 2 (a) we connected the solar water heater with solar still, in which water is circulated naturally. Its specification is gives in table 1.

(a)

(b)

Fig 2: **(a)** Experimental Setup, **(b)** Measuring Instruments Used.

Table 1: Specifications for the Setup

Solar Distillation System			**Additional Solar Pre-Heating Collector**		
S. No	**Component**	**Specification**	**S. No.**	**Component**	**Specification**
1.	Black coated iron sheet thickness	$(0.6071 \times 10^{-3} m)$	1.	Effective Surface area	1.0 m²
2.	Length	1.0 m	2.	Collector Thickness	0.095m
3.	Width	1.0 m	3.	Effective Glass area	1.0 m²
4.	Front height	0.18 m	4.	Glass thickness	0.004 m
5.	Back height	0.61 m			
6.	Glass thickness	0.004 m	5.	Box material	Fiber
7.	Inclination angle of glass (latitude angle)	23º	6.	Inclination angle (latitude angle)	23º
8.	Effective Glass area	1.0 m²	7.	Tubes material	Copper
9.	Surface area	1.0 m²	8.	Number of tubes	9
10.	Water holding capacity	180	9.	Diameter of tubes	0.001m

liters	10. Insulation thickness(Thermo-coal) 0.012m
11. Insulation thickness (thermo-coal) 0.012m	
12. Wooden thickness 0.012m	
13. Plastic flexible pipe length 2.0 m	
14. Distilled water storage tank capacity 5 liters	
15. Measuring jar capacity 1to 2000 ml	

5. Observation and Results

Experiment was conducted in the month of Feb 2016 for three successive days taking three distinct water levels 0.06m, 0.12m & 0.18m respectively. The angle of inclination of the set up is $23^{0.}$ A solar water heater was also attached to solar still in the same angle as that of the still.
Time based reading of water yield was being made & tabulated as shown below:

Table 2: Observations of first day in month of Feb-2016 with water level 0.06 m.

Time (hours)	T_a (°C)	V_w (km/hr)	RH_a (%)	T_v (°C)	T_{wb} (°C)	T_{wt} (°C)	T_{hi} (°C)	T_{ho} (°C)	T_{gi} (°C)	T_{go} (°C)	Yield (ml)	I_{avg} (W/m^2)	Efficiency (%)
7am-8am	17	3ESE	52	18	16	17.3	17	25	17	17	0	54.15	0
8am-9am	19	3SSE	67	26	23.2	24.6	23	33	25.9	22	2	254.55	0.246
9am-10am	24	3S	46	37	31	32.7	32	44	35	31	12	525.55	0.716
10am-11am	27	5SSW	33	46	40.8	42.1	39	50	44.3	36	28	711.95	1.234
11am-12pm	31	5WSW	28	53	48.9	50.8	46	57	52	40	90	847.1	3.334
12pm-01pm	33	5W	22	59	57.9	59.7	54	65	60	48	210	930.35	7.085
01pm-02pm	34	0	20	64	60.1	61.8	60	76	63	46	279	914.1	9.580
02pm-03pm	33	0	21	66	61.7	63.7	61	65	64	45	338	768.3	13.808
03pm-04pm	30	0	22	61	59.9	61.2	..	..	60	44	390	544.35	22.488
04pm-05pm	26	0	26	59	58.1	59.6	..	..	58	43	385	347.05	34.821
05pm-06pm	27	0	30	50	52	53.5			51	35	338	126.95	83.571
06pm-7am											**1171**		
Total											**3243**		

Thermal Efficiency of solar still in sunshine hours (between 7am to 06pm) is 16.08%.

Table 3: Observations of second day in month of Feb-2016 with water level 0.12 m.

Time (hours)	T_a (°C)	V_w (km/hr)	RH_a (%)	T_v (°C)	T_{wb} (°C)	T_{wt} (°C)	T_{hi} (°C)	T_{ho} (°C)	T_{gi} (°C)	T_{go} (°C)	Yield (ml)	I_{avg} (W/m²)	Efficiency (%)
7am-8am	15	6 NNE	69	22	20	21	20	27	19	19	0	76	0
8am-9am	16	6 NNE	77	29	25	27	24	34	23	22	0	238.5	0
9am-10am	21	6 NNE	61	33	29	31	30	40	27	25	12	456	0.826
10am-11am	24	5 NNE	48	35	30.1	33.1	32	43	39	30	22	692.1	0.997
11am-12pm	27	5 NNE	42	42	35.1	40	39	49	45	33	47	874.2	1.687
12pm-01pm	28	6 N	35	48	40.9	46.4	41	50	61	37	98	952.9	3.228
01pm-02pm	29	6 NNW	31	53	46.7	52.5	44	54	61	40	162	941.35	5.401
02pm-03pm	27	6 WNW	37	54	50.2	53.2	50	56	60	39	200	851.65	7.371
03pm-04pm	25	6 WNW	33	54	52.1	53.6	51	56	59	38	263	658.5	12.536
04pm-05pm	23	6 WNW	34	50	51.7	51.8	..	..	48	35	295	392.85	23.570
05pm-06pm	22	3 N	36	48	48.9	49.6	..	..	50	29	333	121.95	85.711
06pm-7am											**1792**		
Total											**3224**		

Thermal Efficiency of solar still in sunshine hours morning (7am) to evening (06pm) is 12.84%.

Table 4: Observations for third day in month of Feb-2016 with water level 0.18 m.

Time (hours)	T_a (°C)	V_w (km/hr)	RH_a (%)	T_v (°C)	T_{wb} (°C)	T_{wt} (°C)	T_{hi} (°C)	T_{ho} (°C)	T_{gi} (°C)	T_{go} (°C)	Yield (ml)	I_{avg} (W/m²)	Efficiency (%)
7am-8am	18	3S	65	32	27.1	30.2	27	34	30	19	0	64.5	0
8am-9am	20	5S	76	35	29.6	31.4	28	36	32	22	0	244.6	0
9am-10am	24	3S	59	38	31.7	37.1	30	40	37	28	8	470.35	0.533
10am-11am	28	3SW	45	43	34.8	42.7	34	47	42	31	18	700.25	0.806
11am-12pm	32	3WSW	38	48	40.7	46.8	38	50	47	35	34	885	1.205
12pm-01pm	33	5W	30	52	46.5	50.9	44	57	51	38	78	961.15	2.547
01pm-02pm	33	5W	25	56	49.4	53.2	46	58	54	41	95	932.75	3.196
02pm-03pm	32	6W	32	57	52.7	55.9	48	58	55	37	155	805.7	6.038
03pm-04pm	28	5N	31	54	54.2	56.4	49	58	52	33	207	621.25	10.458
04pm-05pm	25	5N	35	53	54	54.8	..	..	50	28	240	354.4	21.256
05pm-06pm	27	0	38	50	52.8	53	..	..	49	24	255	92.25	86.766
06pm-7am											**1926**		
Total											**3016**		

International Journal of Research
ISSN: 2348-6848 Vol-3, Special Issue-19
Special Issue on
National Workshop on Emerging Sector of Engineering and Management (NWESEM-2016)

Thermal Efficiency of solar still in sunshine hours morning to evening is 12.07%. As shown in the Fig 3, solar still produces maximum water yield for water level of 0.06 m during a normal sunny day. A water yield is continuous increased till 04pm, after 4pm yield is decreases in subsequent hours.

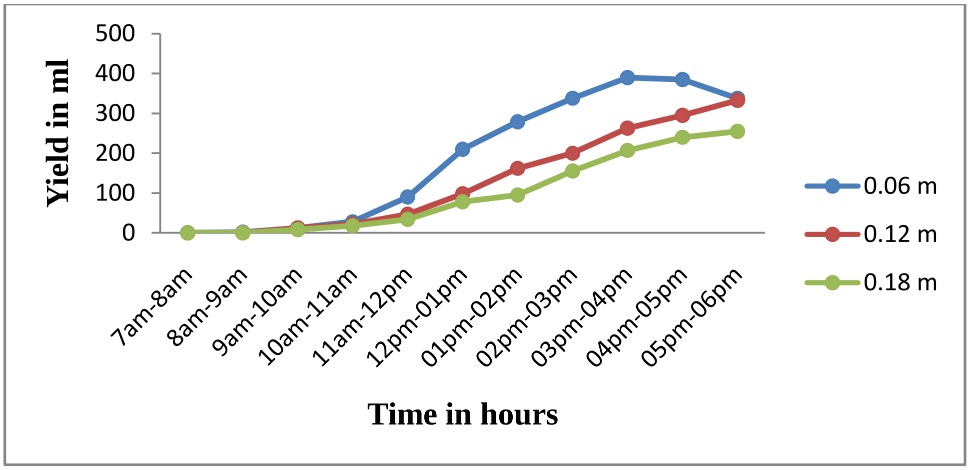

Figure: 3 Yield v/s Time graph of still for three different days with three distinct water levels

As shown in Fig.4, water yield in sunshine hours is more with water level 0.06 m and less with 0.18 m, whereas during evening to next morning this yield reverses i.e. water level 0.18 m more yield as compare to .06 m and 0.12 m during night hours.

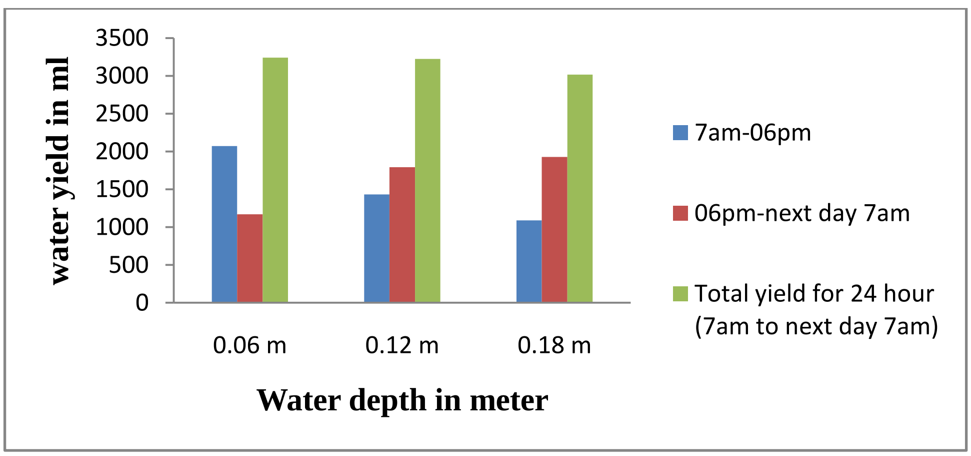

Fig: 4 Hourly variation of water yield in sunshine hours, sunset hours and 24 hours, for distinct water levels.

Following graph represents variation of solar radiation with time for three different days. Variation in radiation almost same, according to graph radiation increase from 7 am to 01pm after that radiation decrease from 01 pm to 06 pm

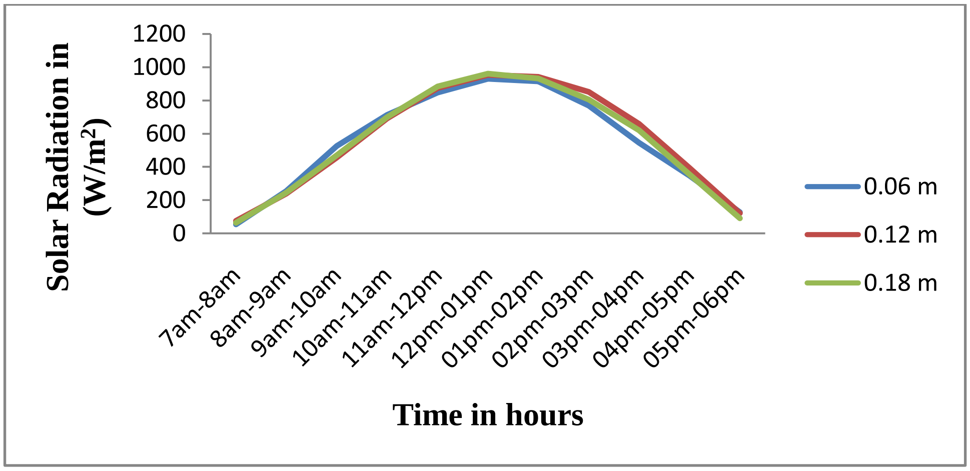

Fig: 5 *Solar Radiation (w/m^2) v/s Time (hours) for three different days and distinct level.*

Fig 6: Show's the hourly efficiency for three distinct water level in this graph the efficiency is continually increase when water level 0.06m use but all three water level during 05pm to 06pm efficiency almost same.

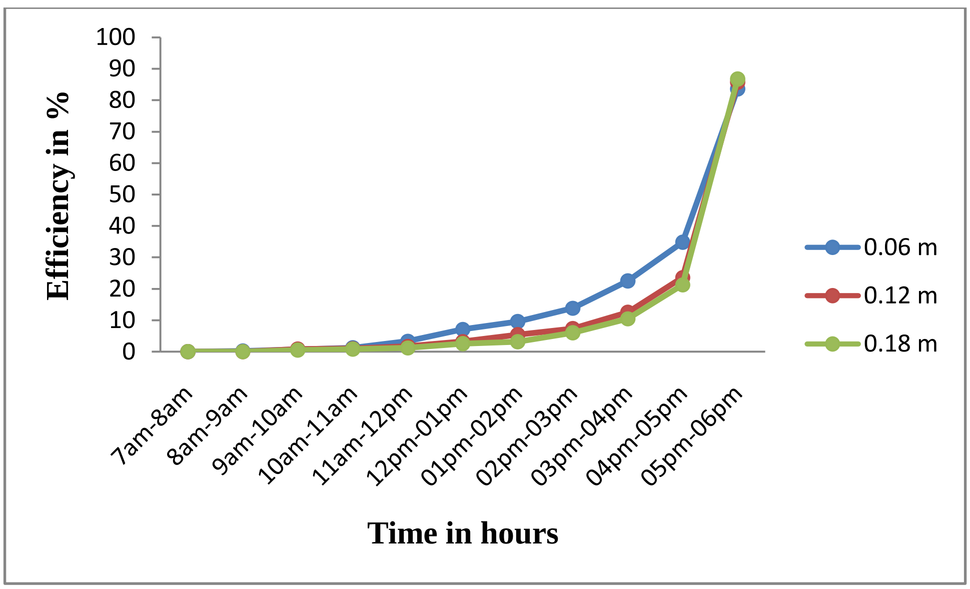

Fig: 6 *Hourly variations in efficiency (%) for three distinct water levels*

6. Water Quality Testing and Analysis

The single slope solar water distillation system with solar water heater has worked successfully and produced purified water, we have done the analysis of purified water in water testing laboratory, Jabalpur-482001 (M.P.) and the result is tabulated below.

- Sample Description: Water samples(untreated and treat)

- Sample volume: 500 ml

Table 5: Analysis report of purified water

Tests Type	Inlet Water	Outlet Water (Distillate)	I. S. Standards
Chemical tests			
pH	7.8	6.8	6.5-8.5
Alkalinity (mg/ L)	26.6	-	200
Turbidity (NTU)	10	5	1
Total Hardness (mg /L)	278	181	200
Dissolved Oxygen (mg /L)	11	11	-
Chlorides (mg/ L)	834	201	250
Sulphates (mg /L)	124	62	200
Total Dissolved Solids (TDS) (mg/ L)	405	229	300
Microbiological tests			
Total plate count (CFU ml^{-1})	430	Nil	-
Coli form count (CFU ml^{-1})	835	Nil	-
Total plate count (CFU ml^{-1})	430	Nil	-

7. Conclusion

- A single slope solar still has been constructed and tested successfully.
- Water quality testing: It is observed that the solar still was efficiently converting impure water into pure drinking water, with TDS value reduced (229 from 405 mg/l), pH is reduced 6.8 from 7.8. An appreciable elimination in microbiological bacteria, without change in dissolve oxygen % is observed. Test proved that the water is as pure as boiled water and there are no harmful salts at all.
- The overall thermal efficiency of solar still in sunshine hours is 16.08%, 12.84% and 12.07% with three water level 0.06m,0.12m and 0.18m.
- The total yield was found 3.243, 3.224 and 3.016 liter with respected water level in 24 hours. The yield of water in sunshine hours is more with water level 0.06m as compare to water level 0.12m and 0.18m, but after sunset during evening to next morning the water yield is more with water level 0.18m as compare to water level 0.12m and 0.06m.
- Addition of solar pre heating collector results in high and continues yield of pure water even after sunset.

Nomenclature

A_w	=	Evaporative surface area (m^2)
As	=	Area of solar still (m^2)
Ac	=	Area of solar water heater/solar collector (m^2)
A_g	=	Area of effective glass surface (m^2)
C_p	=	Specific heat (J/kg ^oC)
d	=	Level of water in (m)
ρ	=	Density (kg/m^3)
k	=	Thermal conductivity (W/m ^oC)
μ	=	Viscosity (Pa s)
β	=	Expansion factor
η	=	Thermal efficiency of solar still (%)

L	=	Latent heat of Vaporization of water (2260 kJ/kg)
P_{ci}	=	Partial saturated Vapor pressure at condensing cover temperature (N/m^2)
P_w	=	Partial saturated vapor pressure at water temperature (N/m^2)
RH_a	=	Humidity in ambient condition (%)
h_{ew}	=	Evaporative heat transfer coefficient (W/m^2 ^{o}C)
h_{cw}	=	Convective heat transfer coefficient (W/m^2 ^{o}C)
I_{avg}	=	hourly average solar radiation on solar still and solar water heater (W/m^2)
T_a	=	Atmospheric temperature (oC)
T_w	=	water surface temperature (^{o}C)
T_{gi}	=	Glass inner temperature, (^{o}C)
T_{go}	=	Glass outer temperature (^{o}C)
T_v	=	vapor temperature (^{o}C)
V_w	=	wind velocity (km/h)
q_{ew}	=	Heat transfer per unit area per unit time (W/m^2)
m_{ew}	=	= Rate of mass transfer, (kg/s)
Pr	=	Prandtl number
Gr	=	Grashoff's number

References

[1] Abdullah AS. "Improving the performance of stepped solar still" Desalination 2013; 319:60–5.

[2] Ragh Vendra Singh, Shiv Kumar, M.M. Hasan, M. Emran Khan, G.N. Tiwari, "Performance of a solar still integrated with evacuated tube collector in natural mode" Desalination 318 (2013) 25–33.

[3] Omar Ansari, Mohamed Asbik, Abdallah Bah, Abdelaziz Arbaoui, Ahmed Khmou, "Desalination of the brackish water using a Passive solar still with a heat energy storage system" Desalination 324 (2013) 10–20.

[4] Z.M. Omara, Mohamed A. Eltawil, "Hybrid of solar dish concentrator, new boiler and simple solar collector for brackish water Desalination" Desalination 326 (2013) 62–68

[5] Dinesh Kumar1, Patel Himanshu2, Zameer Ahmad3, "Performance Analysis of Single Slope Solar Still" International Journal of Emerging Technology and Advanced Engineering (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 3, Issue 3, March 2013)

[6] V. Sivakumar, E. Ganapathy Sundaram, "Improvement techniques of solar still efficiency: A review" Renewable and SustainableEnergy Reviews 28(2013)246–264.

[7] Gajendra Singh, Shiv Kumar, G.N. Tiwari "Design, fabrication and performance evaluation of a hybrid photovoltaic thermal (PVT) double slope active solar still" Desalination 277 (2011) 399–406

[8] K. Sampath kumar, T.V. Arjunan, P. Pitchandi, P. Senthil kumar, "Active solar distillation—A detailed review", Renewable and Sustainable Energy Reviews 14 (2010) 1503–1526

[9] Anil Kr. Tiwari, G.N. Tiwari, ―Thermal modeling based on solar fraction and experimental study of the annual and seasonal performance of a single slope passive solar still: The effect of water depths‖, Desalination 207 (2007) 184–204.

[10] Rajesh Tripathi, G.N. Tiwari, ―Thermal modeling of passive and active solar stills for different depth of water by using the concept of solar fraction‖, Solar Energy 80 (2006) 956–967.

[11] Tiwari GN, Tiwari AK. "Solar distillation practice for water desalination systems". New Delhi: Anamaya Publishers; 2008.

[12] Tiwari GN. "Solar energy: fundamentals, design, modelling and application" New Delhi: Narosa Publishing House; 2004. p. 278–306.

[13] Malik MAS, Tiwari GN, Kumar A, Sodha M S. "Solar distillation" Oxford, UK: Pergamon Press; 1982. P.8–17.

[14] Dunkle RV. "Solar water distillation, the roof type solar still and a multi effect diffusion still", International developments in heat transfer, ASME Proceedings of International Heat Transfer, University of Colorado. 1961;5:895–902.

[15] M.K. Ghosal, GN. Tiwari, N.S.L. Srivastava, Thermal modeling of a controlled environment greenhouse cum solar distillation for composite and warm humid climates of India‖ Desalination 15 1 (2002) 293-308

[16] Omar O Badran, Mazen M Abu-Khader. "Evaluating thermal performance of a single slope solar still" Heat Mass Transfer 2007; 43:985–95.