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Performance Enhancement in Working of Single Slope Solar Still using Different Modifications

Khoob Singh [a] *, Harish Kumar [b], Manish Kumar [b]
[a] Department of Mechanical Engineering, K.ITPS Moradabad, Uttar Pradesh, India
[b] Department of Mechanical Engineering, Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, India

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Abstract

As the population is increasing, fresh water resources are under heavy pressure. A very small fraction, about 3 percent of the available water resources is available as fresh water. Drinking water shortage is expected to become one of the biggest problems for humanity. Many developing countries like India have given topmost priority to fresh water supply in their rural development plans. Distillation is an universal method by which all types of contaminants at any concentration level can be removed. Solar distillation is a method which is energy independent and energy is available free of cost in form of solar radiation. The categorization of solar stills is on the basis of Passive and Active solar stills, basic difference being in case of active solar stills is that in the later the temperature difference between the evaporative and condensing surfaces are increased by feeding the additional thermal energy from the flat plate collector in to the bottom of solar still. The objective of the work is to fabricate a Single slope solar still and to study the affects of various process parameters on the performance of solar still, economic viability, cost of distillate, energy balance of solar still and comparison of experimental results for solar still on periodic (hourly, daily & monthly) basis.

1. Introduction

Fresh water is basic needs of human and without this life will be impossible. About 70 percent of the total water available on earth is fresh water. Out of this , only 1 percent is accessible as surface freshwater while the rest 2 percent is locked away in the form of ice caps and glaciers in the Polar Regions, for distant from human habitation. At the current trend of growth, global population is expected to reach 8 billion by 2025 and the per capita water available will come down. The average amount of fresh water per capita may still be enough to meet human needs, if it is properly distributed. But equitable distribution is not possible due to mainly two reasons. The first is: two-thirds of the global population (around 4 billion) lives in areas receiving only one- fourth of the global annual rainfall and the second is that the rainfall is not uniform throughout the seasons and from year to year. Supply of potable water to all is the biggest challenge before the world today. Limited resources have resulted in water shortage in 88 developing countries across the world containing 50% of the world's population. Further water supply in these countries cannot meet urban and industrial development needs as well as associated changes in lifestyle.

India is a case in point. From a per capita annual average of 5,177 m3, fresh water availability in India dropped to 1,820m3 in 2001. It is predicted that by 2025, per capita annual average fresh water availability will be approximately 1,340 m3 (CPCB (2000)). As the demand for water increases so does the cost. Caught between the growing demands for fresh water on one hand, and increasing pollution of water on the other, India is one of the countries in the world facing a severe water crisis.

Corresponding Author,
E-mail address: harry.mit2007@gmail.com

2. Solar Distillation System

2.1 Principle

In a simple solar still, solar radiation passes through the glass cover. This solar energy is almost entirely absorbed by the black cover on the basin while it is partially absorbed in the thin saline water layer. Thus, saline water and basin are heated by the solar energy. The heat is convected from the black surface into the saline water and the temperature of the saline water increase. Vaporization takes place at the interface, saline water surface and air inside of the solar still, at the interface temperature ti. Interfacial area, saline water surface is semi permeable. A plane is called semi permeable when the mass flux of one component is zero. Such a plane is, for instance, the surface of water, which evaporates into an adjoining air steam. Thus, at the interface, the saturated air at the temperature, ti, is transported by diffusion due to the partial pressure difference and convection due to the natural convection of the humid air from the interface into the air inside of the solar still with the temperature tr. In steady state or quasi-steady state conditions, the air inside of the solar still is also saturated at the temperature, tr. Therefore, the humid saturated air inside of the solar still will condense at the glass cover, which has a lower temperature, tg than the air temperature inside solar still, tr. Heat of condensation heats the glass cover. The glass cover exchanges heat with surrounding and air inside the still by convection and radiation. The condensate flows down, collecting along the glass cover and then in a channel at the end of the glass cover on the south side of the still. Finally, it is collected in a storage bottle outside of still. The schematic view of the solar still is shown in Fig. 2.1. In order to calculate the daily produced condensed water and efficiency, energy balance method has been applied by making the following assumptions:

- The whole system is in a quasi-steady state condition.
- Heat loss by radiation from the circumferential area is negligible.
- At the base of the sill, temperatures of the walls equal to the water temperature, and the water temperature is the average of the interface temperature, ti and the bottom temperature, tb
- The wind speed is assumed to be constant during the experiment.

The performance of a solar still is generally expressed as the quantity of water evaporated by unit area of the basin in one day, i.e. cubic meters or liters of water per square meter of the basin area per day. This performance of solar still can be predicted by deploying the energy and mass balance equations on the various components of the still. The whole system is in a quasi-steady state condition and the temperatures are assumed not to change in one hour interval of time. The energy balance equations for the whole still glass cover, saline water interface and black plate at the bottom has also been done.

2.2 Solar Stills

Most of distillation systems have been abandoned due to very slow production rate as per documented literature survey, however, research in the area of solar distillation is limited in the following academic organizations namely Central Arid Zone Research Institute (CAZRI), Jodhpur, IIT Delhi, and Sardar Patel Renewable Energy Research Institute (SPRER), Anand (India); RYUKYUS, NAGOYA and CHUO Universities (Japan); UNAM Ciudad Universitaria, Coyoacaan (Mexico); ALEXANDRIA University (Egypt); BEN-GURION University of the Negev (Israel); TECHNISCHE Universitat Bergakademie Freiberg (Germany); Jordan University of Science and Technology, Irbid (Jordan); University of Ouargla (Algeria); XiAn Jiao Tong University (China); University of Foggia (Italy); National Centre for Scientific Research (NCSR) "DEMOKRITOS" Laboratory for Solar and other Energy Systems (Greece) .

2.3 Methodology

Solar distillation is one of the available methods for water distillation and sunlight is one of several forms of heat energy that can be used to power that process. The idea behind a solar still is very simple: saline water inside a black painted basin enclosed in a completely air tight area formed by a transparent cover is heated up and evaporated due to incident solar irradiance that passes though the transparent cover. Consequently water vapour is directed upward and condenses in pure water as it comes in contact with the cooler inside surface of the cover. The energy that the water absorbs contributes to the temperature rise of the water, which leads to evaporation. Evaporation is a process that occurs when the water molecules on the surface of the water obtain enough kinetic energy to change from the liquid to vapour state. The evaporated molecules add to the water vapour between the glass and the water and create a large temperature difference. This difference in temperature affects the temperature of the water vapour that is inside the still between the glass and the water, which creates natural convection.

A higher temperature difference encourages more convection. The warm water vapour will tend to rise towards the cooler glass cover. When the water vapour comes in contact with the glass, it will condense because the water molecules will lose the kinetic energy needed to be in the vapour state. Since the glass is angled, gravity will cause the condensed water to flow down towards the collection trough.

Despite the advantage of solar stills, their most important drawback is low water productivity or performance in comparison with other thermal desalination methods and to high land requirement. This happens since productivity rate of solar stills depends on the available solar radiation. For this, research activities nowadays move in the direction towards increasing performance and output of solar stills by using several techniques. These are all targeted on the concept of increasing the difference between saline water temperature and glass cover temperature. The view of the solar still and its technical specifications can be seen in Table 2.1 respectively.

Table: 1. Technical Specifications of Single Slope Taper Solar Still

Length	6ft
Width	3ft
Cover inclination	15 °
Glass cover area	$1.65 m^2$
Absorber plate area	$1.59 m^2$
Glass Thickness	5mm
Water depth	2cm

Fig: 1. View of Single Slope Solar Still

For calculation of Flux I_T on tilted surface at any instant

$$I_T = I_b r_b + I_d r_d + I_g r_r \tag{1}$$

Where

$$r_b = \frac{\sin\delta.\sin(\phi-\beta)+\cos\delta.\cos\omega.\cos(\phi-\beta)}{\sin\phi.\sin\delta+\cos\phi.\cos\delta.\cos\omega} \tag{2}$$

For the tilted surface facing due south ($\gamma = 0$)

$$r_d = \frac{1+\cos\beta}{2} \tag{3}$$

And

$$r_r = \frac{\rho(1-\cos\beta)}{2} \tag{4}$$

δ In degrees is given by the following relation

$$\delta = 23.45\sin\left[\frac{360(284+n')}{365}\right] \tag{5}$$

For calculation of I_g

Taking Isc = 1.367 kW/m^2

$$H_o = \frac{24\times I_{sc}\times 3600}{\Pi}\left[1+0.033\cos\frac{360n'}{365}\right] \quad (6)$$

$$\left(\omega_s \sin\phi.\sin\delta + \cos\phi.\cos\delta.\sin\omega_s\right)$$

[in kJ/m^2-day]

$$\therefore \quad \frac{\overline{H_g}}{\overline{H_o}} = \left[a + b(\frac{S}{S_{\max}})\right] \quad (7)$$

$$S_{\max} = \frac{2}{15}\omega_s \quad (8)$$

$$\omega_s = \cos^{-1}\{\tan(\phi-\beta).\tan\delta\} \quad (9)$$

ω_s = Sunrise hour angle

Constants a and b in equation are taken from weather data given by Modi and Sukhatme (1979).

We have assumed that the values of a = 0.25 and b = 0.57 for New Delhi are valid for Moradabad.

$$\frac{\overline{H_d}}{\overline{H_g}} = 1.411 - 1.696\left[\frac{\overline{H_g}}{\overline{H_o}}\right] \quad (10)$$

The hourly extraterrestrial radiation on a horizontal surface (I_o) is obtained by calculating the instantaneous value at the mid point of time intervals and multiplying by 3600 s i.e

$$I_o = I_{sc}\times 3600\left[1+0.033\cos\frac{360n'}{365}\right]\left(\sin\phi.\sin\delta + \cos\phi.\cos\delta.\cos\omega\right)$$

[kJ/m^2-h] (2.11)

The relationship for diurnal variation of the monthly average hourly global radiation at a location is given by

$$\frac{\overline{I_g}}{\overline{H_g}} = \frac{\overline{I_o}}{\overline{H_o}}\left(a_1 + b_1\cos\omega\right) \quad (12)$$

Where

$$\left\{a_1 = 0.409 + 0.5016\sin\left(\omega_s - 60^\circ\right)\right\}$$
$$\left\{b_1 = .6609 - .4767\sin\left(\omega_s - 60^\circ\right)\right\} \quad (13)$$

For estimating the monthly average hourly diffuse radiation

$$\frac{\overline{I_d}}{\overline{H_d}} = \frac{\overline{I_o}}{\overline{H_o}} \quad (14)$$

$$\therefore \quad I_b = I_g - I_d \quad (15)$$

Table: 2. Calculation of Efficinecy of Solar Still Taking Sample Set Of Data (Without Insulation)

Date: 10thJune2014

Time in hours	Product from still m_w [kg/hr]	Atm. temp (^{0}C) (t_a)	Temperature (^{0}C) Moist air temperature (t_r)	Glass Surface temperature (t_g)	Water level interface temperature (t_i)	Bottom temperature (t_b)	η_i
12-13	0.51	37	50	48	52	59	25.72

Calculations

Latitude ϕ = 28.58

No of days n' = 161

Declination $\delta = 23.45\sin\left[\frac{360(284+161')}{365}\right]$

δ = 23.011^0

Slope of the glass to the horizontal is taken as 15^0

$$\omega_s = \cos^{-1}\{-\tan(\phi-\beta).\tan\delta\}$$

$$\omega_s = \cos^{-1}\{-\tan(28.58-15).\tan-23.0110\}$$

ω_s = 95.871^0

ω_s = 1.672

$$S_{\max} = \frac{2}{15}\omega_s$$

=2/15 x 95.871

$S_{\max}$ = 12.78hours.

let S= 7hours.

Now

$$H_o = \frac{24\times I_{sc}\times 3600}{\Pi}\left[1+0.033\cos\frac{360n'}{365}\right]\left(\omega_s\sin\phi.\sin\delta + \cos\phi.\cos\delta.\sin\omega_s\right)$$

$$= \frac{24\times 1.367\times 3600}{\Pi}\left[1+0.033\cos\frac{360\times 161}{365}\right]$$

$$\left(1.672\times\sin 28.58.\sin(23.011) + \cos 28.58.\cos(23.011).\sin 95.871\right)$$

H_o =40639.76 kJ/m^2-hr

Or H_o = 11.28 kW/m^2-hr

$$\frac{\overline{H_g}}{\overline{H_o}} = \left[a + b(\frac{S}{S_{\max}})\right]$$

Where a = 0.25, b = 0.57

$$Hg = \frac{8.915 \text{ x } (0.25+ 0.57) \text{ x } 10}{12}$$

Hg = 0.454 KW/m^2 hr

$$\frac{\overline{H_d}}{\overline{H_g}} = 1.411 - 1.696\left[\frac{\overline{H_g}}{\overline{H_o}}\right]$$

$$= 1.411 - 1.696\left[\frac{6.36}{11.28}\right]$$

H_d = 2.892 KW/m^2 –hr

$$r_d = \frac{1+\cos\beta}{2}$$

= 0.98

$$r_r = \frac{\rho(1-\cos\beta)}{2}$$

Taking ρ= .2

r_r = 0.017

For 12:00 to 13:00 hours.

ω = 15(12-time in hours)

ω = 15(12-12.5)

ω = -7.5^0

$$I_o = I_{sc} \times 3600\left[1+0.033\cos\frac{360n'}{365}\right] \text{ [kJ/m}^2\text{-h]}$$

$$\left(\sin\phi.\sin\delta + \cos\phi.\cos\delta.\cos\omega\ \right)$$

$$I_o = 1.367 \times 3600\left[1+0.033\cos\frac{360\times161}{365}\right]$$

$$\left(\sin 28.58.\sin(23.011) + \cos 28.58.\cos(23.011).\cos(-7.5)\right)$$

= 4663.18 kJ/m^2-hr

=1.295 kW/m^2-hr

For Global hourly radiation:-

$$\frac{I_g}{H_g} = \frac{I_o}{H_o}\left(a_1 + b_1\cos\omega\right)$$

Where

$$\left\{a_1 = 0.409 + 0.5016\sin\left(\omega_s - 60^\circ\right)\right\}$$

$$\left\{b_1 = .6609 - .4767\sin\left(\omega_s - 60^\circ\right)\right\}$$

By substituting ω_S =95.871 in above equations we get

a $_=$ 0.702 and b$_1$=0.3815

I_g / 6.34 = 1.295/11.28 (.702+ .381 .cos-7.5)

I_g = 0.785 kW/m^2-hr

Now For hourly diffuse radiation

$$\frac{I_d}{H_d} = \frac{I_o}{H_o}$$

I_d =1.295x2.892/ 11.28

I_d = 0.332kW/m^2-hr

$$r_b = \frac{\sin\delta.\sin(\phi-\beta) + \cos\delta.\cos\omega.\cos(\phi-\beta)}{\sin\phi.\sin\delta + \cos\phi.\cos\delta.\cos\omega}$$

$$r_b = \frac{\sin(23.011)\sin(28.58-15) + \cos(23.011).\cos(-7.5).\cos(28.58-15)}{\sin 28.58.\sin(23.011) + \cos 28.58.\cos(23.011).\cos(-7.5)}$$

$= 0.990$

r$_b$= 0.990

I_b = I_g - I_d

I_b =0.785-0.332=0.453 kW/m^2-hr

So, total radiation on tilted surface

$$I_t = I_b\,.\,r_b + I_d\,.\,r_d + I_g\,.\,r_r$$

We get

I_t =0 .453×0.990 + 0.332×0.98 + 0.785×.017

I_t = 0.790 kW/m^2-hr

$$\eta_a = \frac{0.51\times 2368}{3600\times 0.790\times 1.65} \times 100$$

= 25.72 %

3. Distillate Produced on Hourly Basis with Insulation

Table: 3. Calculation of Efficinecy of Solar Still Taking Sample Set Of Data (With Insulation)

Date: 20th June 2014

Time in hours	Product from still m$_w$ [kg/hr]	Atm. temp (^{0}C) (t$_a$)	Temperature (^{0}C)				η_i
			Moist air temp(t$_r$)	Glass Surface temperature (t$_g$)	Water level interface temperature (t$_i$)	Bottom temp(t$_b$)	
12-13	0.67	38	50	49	52	58	33.72

Calculations

Latitude ϕ = 28.58

No of days n’ = 171

$$\text{Declination } \delta = 23.45\sin\left[\frac{360(284+171)}{365}\right]$$

δ = 23.440

Slope of the glass to the horizontal is taken as 15^0

$$\omega_s = \cos^{-1}\left\{-\tan(\phi-\beta).\tan\delta\right\}$$

$$\omega_s = \cos^{-1}\left\{-\tan(28.58-15).\tan 23.44\right\}$$

ω_S = 95.98^0

ω_S =1.674 radian

$$S_{\max} = \frac{2}{15}\omega_s$$

=2/15 x 95.98

$S_{\max}$ = 12.797hours.

Let S = 7 hours.

Now

$$H_o = \frac{24\times I_{sc}\times 3600}{\Pi}\left[1+0.033\cos\frac{360n'}{365}\right]$$

$$\left(\omega_s\sin\phi.\sin\delta + \cos\phi.\cos\delta.\sin\omega_s\right)$$

$$=\frac{24\times1.367\times3600}{\prod}\left[1+0.033\cos\frac{360\times171}{365}\right]$$

$$\left(1.674\times\sin28.58.\sin\left(23.44\right)+\cos28.58.\cos\left(23.44\right).\sin95.98\right)$$

H_o = 40654.50 kJ/m^2-hr

Or H_o =11.299 kW/m^2-hr

$$\frac{\overline{\overline{H_g}}}{H_o}=\left[a+b(\frac{S}{S_{\max}})\right]$$

Where a = 0.25, b = 0.57

$$Hg=\frac{11.299 \text{ x } (0.25+ 0.57) \text{ x } 10}{12}$$

Hg = 6.349KW/m^2 hr

$$\frac{\overline{\overline{H_d}}}{H_g}=1.411-1.696\left[\frac{\overline{\overline{H_g}}}{H_o}\right]$$

$$=1.411-1.696\left[\frac{6.349}{11.299}\right]$$

H_d = 2.896KW/m^2 -hr

$$r_d=\frac{1+\cos\beta}{2}$$

r_d =0.98

$$r_r=\frac{\rho(1-\cos\beta)}{2}$$

Taking ρ= .2

r_r = 0.017

For 12:00 to 13:00 hours.

ω = 15(12-time in hours)

ω = 15(12-12.5)

ω = -7.5^0

$$I_o=I_{sc}\times3600\left[1+0.033\cos\frac{360n'}{365}\right] \text{[kJ/m}^2\text{-h]}$$

$$\left(\sin\phi.\sin\delta+\cos\phi.\cos\delta.\cos\omega\right)$$

$$I_o=1.367\times3600\left[1+0.033\cos\frac{360\times171}{365}\right]$$

$$\left(\sin28.58.\sin(23.44)+\cos28.58.\cos(23.44).\cos(-7.5)\right)$$

I_o =4700.58 kJ/m^2-hr

= 1.305kW/m^2-hr

For Global hourly radiation:-

$$\frac{\overline{\overline{I_g}}}{H_g}=\frac{\overline{\overline{I_o}}}{H_o}\left(a_1+b_1\cos\omega\right)$$

Where

$$\left\{a_1=0.409+0.5016\sin\left(\omega_s-60^\circ\right)\right\}$$

$$\left\{b_1=.6609-.4767\sin\left(\omega_s-60^\circ\right)\right\}$$

By substituting ω_s =90.58 in above equations we get

a= .703and b1=0.380

$$\frac{\overline{\overline{I_d}}}{H_d}=\frac{\overline{\overline{I_o}}}{H_o}$$

I_g / 6.49 = 1.172/8.919 (.662 + .42 .cos-7.5)

I_g = 0.791kW/m^2-hr

Now For hourly diffuse radiation

$$r_b=\frac{\sin\delta.\sin(\phi-\beta)+\cos\delta.\cos\omega.\cos(\phi-\beta)}{\sin\phi.\sin\delta+\cos\phi.\cos\delta.\cos\omega}$$

I_d =1.3.5x 2.896/ 11.299

I_d = 0.334kW/m^2-hr

$$r_b=\frac{\sin(23.44)\sin(28.58-15)+\cos(23.44).\cos(-7.5).\cos(28.58-15)}{\sin28.58.\sin(23.44)+\cos28.58.\cos(23.44).\cos(-7.5)}$$

$=0.987$

r$_b$= 0.987

I_b = I_g - I_d

I_b = 0.791- 0.033 = 0.457kW/m^2-hr

So, total radiation on tilted surface

I_g r_r

$I_t = I_b . r_b + I_d . r_d + I_g . r_r$

We get

I_t = 0 .457×0.987 + 0.334×0.98 + 0.791×0.017

I_t = 0.791kW/m^2-hr

$$\eta_a=\frac{0.67\times2368}{3600\times0.791\times1.65}\times 100$$

= 33.73%

4. Results and Discussion

Table: 4. Hourly Temperatures and Distillate Produced Without Insulation

Date**:** 10thJune2014

Time in hours	**Product from still**	**Atm. temp**	**Temperature (°C)**	η_i

	m_w [kg/hr]	**(°C) (t_a)**	**Moist air temperature(t_r)**	**Glass Surface temperature (t_g)**	**Water level interface temperature(t_i)**	**Bottom temperature (t_b)**	
9-10	0.14	25	49	48	49	51	9
10-11	0.34	29	50	46	51	55	10.21
11-12	0.50	35	52	49	53	60	20
12-13	0.51	37	50	48	52	59	25.72
13-14	0.44	35	49	42	53	55	30
14-15	0.32	32	42	36	50	51	32
15-16	0.10	31	40	32	48	49	35

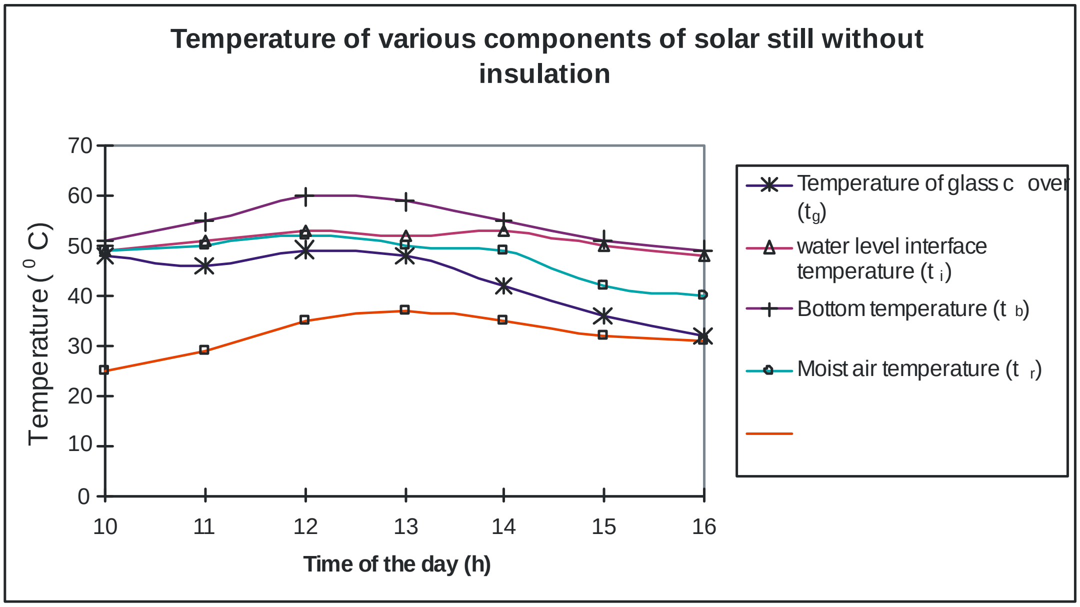

Fig: 2. Temperature of Various Components of Solar Still Without Insulation

Table: 5. Hourly Temperatures and Distillate Produced with Insulation

Date: 20th June 2014

Time in hours	**Product from still m_w [kg/hr]**	**Atm. temp (°C) (t_a)**	**Temperature (°C)**				**η_i**
			Moist air temp(t_r)	**Glass Surface temperature (t_g)**	**Water level interface temperature (t_i)**	**Bottom temp(t_b)**	
9-10	0.14	26	50	49	48	51	15
10-11	0.40	30	51	47	51	54	17
11-12	0.52	36	52	48	53	60	30
12-13	0.67	38	50	49	52	58	33.72
13-14	0.46	35	49	37	52	55	38.5
14-15	0.36	33	41	36	50	52	41
15-16	0.15	31	40	32	47	50	42.5

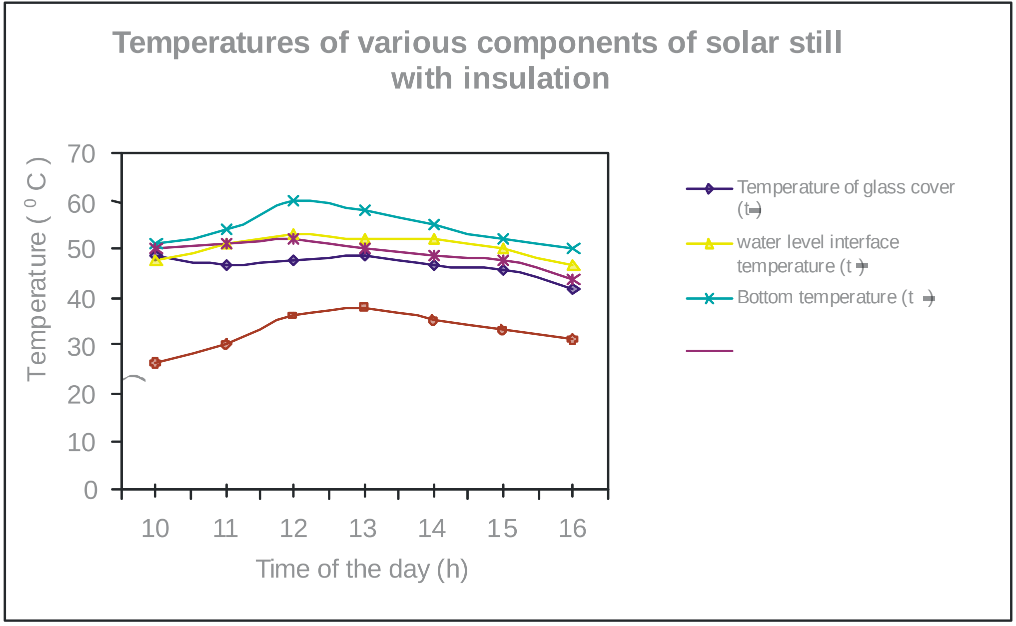

Fig: 3. Temperature of Various Components of Solar Still with Insulation

References

[1] A. A. Al-Karaghouli, W. E. Alnaser, Performance of single & double solar stills, J. Appli. Energy, 78, 2004, 347-354

[2] Z. S. Abdel-Rehim, A. Lasheen Impoving the performance of the solar desalination systems. Renew Energy 2005, 30:1955-71

[3] A. I. Pinar, A. Gurbuz, Theoretical and experimental investigations on solar distillation of IZTECH campus Area Sea water, Desalination, 208, 2007, 169-180

[4] A. Hanson, W. Zachritz, K. Stevns, L. Mimbela, R. Polka, L. Cisneros, Distillate water quality of a single basin solar still: Laboratory and field studies, Sol. Energy, 76, 2004 635-645

[5] M. Farid, F. Hamad Performance of a single-basin solar still. Renew Energy, 1973, 3, 75-83.

[6] P. H. Gleick, Basic Water Requirment for Human Activities: Meeting Basic Needs, International Water, 21(2), 83-92.

[7] G. N. Tiwari, S. Sinha, Energy Convers. Mgmt, 34, 209 1993