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PERFORMANCE ENHANCEMENT IN WORKING OF DOUBLE SLOPE SOLAR STILL WITH MODIFICATIONS

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Abstract— The demand of fresh water is increasing steadily with growing populations. As the population increasing fresh water resources are decreasing day by day. Only a small fraction about 3 % fresh water is available for drinking and it is the biggest problem of world. For solving this type of problem new fresh water source should be discovered and new desalination techniques should be developed. The main water desalination or purification methods are distillation, electro dialysis and reverse osmosis. Electro dialysis and reverse osmosis are more economical for bigger system but for smaller ones solar stills could be preferred because of low cost. On the earth where underground water is not readily obtainable and transportation cost is high in these situations we can produce fresh water from saline water using solar energy i.e. easily available and free of cost. Water distillation is a suitable technique for fresh water production from saline and brackish water with the help of solar energy. The objective of the work is to fabricate a Double slope solar still and to study the effects 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. The work has been further extended on enhancement of distillate output by injecting the dye.

Keywords— *Solar still, Desalination, Saline water, Performance, Absorber Plate, Catch Basin.*

INTRODUCTION

All desalination methods require fossil fuel or electrical energy but solar distillation is a process that can be used to produce fresh water by use of the heat from the sun directed into a simple water purifying equipment. The equipment is commonly called a solar still (Tiwari & Tiwari, 2007). Solar desalination could be one of the most successful applications of solar energy in most of the hot climate countries having limited resources of fresh water (Argaw, 2001). Solar still which uses the principle of evaporation and condensations are able to remove bacterial and chemical pollutants at a low cost (Velmurugan, 2008). In recent years, engineers have conducted experiments on solar stills, to improve its efficiency and the output. Some of the factors of importance were found to be mainly solar radiation, number of sunny hours and the design of the still (Abdallah et al., 2008). The study has focused on the design, fabrication and characterization of double sloped solar stills, which seek to meet the criteria of sustainability while producing safe and clean drinking water for the local peoples. Some of the design factors of importance in the study include water depth, surface area, colour of the basin, inclination of the glass, insulation, materials, temperature of the water, air-tightness, wind velocity and temperature differences in the still and ambient air (Velmurugan et al., 2008.) 8 Some of the useful research work related to this research has been conducted in Baghdad and in Faryab in Afghanistan (Kolstad, 2014). In Baghdad, three solar stills were tested. All had black basins, and two of the stills had additionally jute wicks and in Faryab in Afghanistan three solar still types namely single slope, double chamber, double sloped solar still and wick type solar still were tested and evaluated (Kolstad, 2014). Mwamburi (2012), in her study of factors affecting access to water supply in Kisauni area, Mombasa County, Kenya, found that water shortage is high in Mombasa county and recommended that evaluation of a cost effective solar still was the solution to the water crisis.

LITERATURE REVIEW

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THEORETICAL OPERATIONS OF SOLAR STILLS - EVAPORATION AND CONDENSATION:

The solar distillation systems are classified into two groups; passive and active solar stills, (Fath, 1998). The Principles of operation are the same for all solar stills. The basic principle behind solar distillation replicates the natural process of water purification; evaporation (Badran, 2007). Evaporation of water requires energy. The sun, through direct, diffuse and reflected radiation, supplies this energy to the solar still. A solar still is an air tight basin that contains saline or contaminated water (i.e. feed water). Usually, the basin of the still is filled with brackish or sea water, the incident solar radiation is transmitted through the transparent cover and is absorbed by a black surface (basin). 9 From a radiative point of view, the following happens inside the distiller unit: Solar radiation that is not reflected nor absorbed by the cover is transmitted inside the solar still, where it is further reflected and absorbed by the water mass. The amount of solar radiation that is absorbed is a function of the absorptivity and depth of the water. The remaining energy eventually reaches the blackened basin liner, where it is mostly absorbed and converted into thermal energy. Some of this energy might be lost due to poor insulation of the sides and bottom. At this stage, the water heats up, resulting in an increase of the temperature difference between the cover and the water. Heat transfer takes place as radiation, convection and evaporation from the water surface to the inner part of the inclined glass cover. The evaporated water condenses and releases latent heat (Tiwari & Singh, 2004).

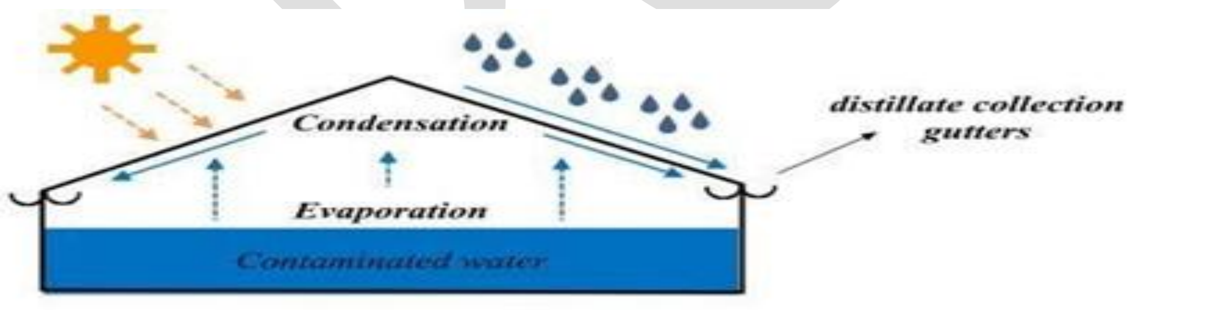

Figure 1: Passive solar still; Source: (Murugavel et al., 2008).

To maximize incoming radiation, the inclination of the glass and latitude should be the same. This will give maximum received radiation in a whole year. In the summer period, the declination angle of the sun is at its highest, due to the tilt of the earth on its axis of rotation thereby; having a lower inclination of the glass will increase incoming radiation to the still in the summer period (Al-Hinai et al., 2002).

As the water is heated, the water bonds that are keeping the water molecules together breaks, making it evaporate. The vapour transfers from the basin, towards the cooling glass by convection and evaporation and condenses to water droplets due to adhesion and cohesive forces in glass and water molecules. Since there is a linear relationship between latent heat of evaporation and the surface tension of liquid, evaporation rate increases with increase in latent heat (Armenta-Deu, 1997). The condensed water (i.e. the distillate) trickles down the cover and is collected in an interior trough and then stored in a separate basin (Al-Hayek & Badran, 2004; Tiwari et al., 2003). As the vapour condenses it releases latent heat (Tripathi et al., 2004). The total amount of energy required to change the water into vapour is termed as the latent heat of vaporization (L). And is calculated as shown in Equation (1) (Arnell, 2002).

$L = 2.501 - 0.0002361T$ [MJ /kg]…………………………………… **Equation (1)**

As seen in the Equation (1), the energy required is dependent on temperature, in degrees Celsius.

There will be no evaporation if the air is saturated. The vapour pressure deficit (VPD) refers to the amount of moisture in the air, and how much moisture the air can hold when it is saturated. This value increases with temperature, and when exceeded, the dew point is reached. For open water surfaces, the evaporation rate increases with the speed of the wind, thereby leading the saturated air away, and bringing new unsaturated air to the surface. Together, the humidity and turbidity control how the water vapour can diffuse into the surrounding (Arnell, 2002).

For the water vapour to condense into liquid, cooling the air to its dew point, or oversaturating the air with vapour makes it to condense. The glass cover is the condenser in a solar still, and it is therefore important to have a temperature difference between the air inside and outside the still.

The salinity of the water also affects the evaporation rate. As the salinity increase, the evaporation rate decrease, because of the salt occupying space in the water, makes fewer molecules available for evaporation. This is why saline water has a higher saturation vapour pressure than fresh water (Arnell, 2002). Ward et al. (2000), however, found this effect to be small, about 2 – 3% lower evaporation rate for saline water over fresh water. Akash et al. (2000), found that increasing the salinity percentage by 10 to 75 %, gave a decrease in output by 1.5 litres/day.

It is important that the still is airtight, due to heat loss to the ambient air. The outcome of a still, therefore, depends on both weather conditions and the design of the still. Weather conditions such as solar radiation, temperature and wind velocity are important factors that affect the outcome (Murugavel et al., 2008). Radiation and how it is distributed through the day is the most important parameter to increase the yield of a solar still (Ray et al., 2011). To estimate the output of a solar still, the following Equation (2) can be used (Twidell and Weir, 2006; Badran and Abu-Khader, 2007):

$$Q = \frac{E x G x A}{L} \quad \textbf{Equation (2)}$$

Where E = efficiency L = Latent heat, A = area of still, G= daily/annual global horizontal solar radiation (MJ/m2), and Q is daily output of water from double slope solar still.

Equation (2) above can be used both prior and post experiments, to predict the outcome. A solar still normally has an efficiency ranging between 30 – 60 %, depending on materials and design (Twidell & Weir, 2006; Badran & Abu-Khader, 2007).

ANALYSIS OF DOUBLE SLOPED SOLAR STILL:

This is a basin type solar still with a triangle shaped glass. The glass is attached to the basin and two distillation pipes collect the condensed water, on each side of the rectangular glass to the bucket. The basin is usually made of a good insulator of heat and painted black to avoid heat losses. An absorber plate is usually used which is black in colour to absorb all incident radiations to the still.

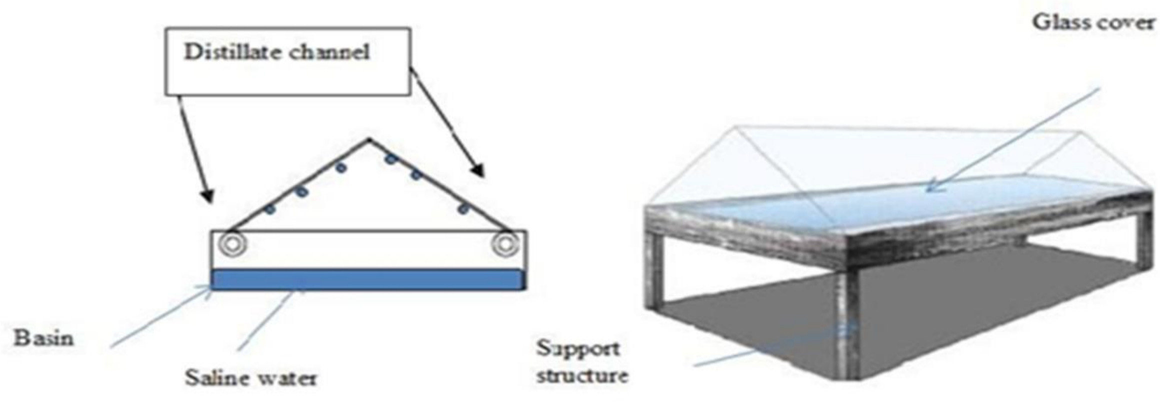

Figure 2: Structural design of a double sloped solar still.

FACTORS AFFECTING DOUBLE SLOPE SOLAR STILL DESIGNS AND FABRICATION:

The productivity of a solar still is affected by ambient conditions (temperature, the insulation, and the velocity of the wind), operating conditions (depth of the water, the orientation of the still and the inlet temperature of the water) and design conditions (material selection for the still and cover, slope of the cover, gap distance and the numbers of covers used).

1. **Latitude.**

Latitude is one of the factors that determine whether single or double slope still should be used. At latitudes higher than 20°, single slope stills with equator facing cover are recommended (Murugavel et al., 2008). For the study area, which is located at a latitude of 4°, double sloped solar still can be successfully used. When the cover is placed with an inclination equal to the latitude angle, it will receive the sun rays close to normal throughout the year (Kabeel & El-Agouz, 2011; Khalifa, 2010). In this way, maximum interception is achieved. However, fundamental in the design is that the distillate condenses on the top cover as a film rather than as droplets. Droplets might otherwise drop back into the feed water and represent a loss of output. To prevent this from happening, the cover should be set at an angle of 10º. This has been observed experimentally by various investigators that the minimum inclination of the glass cover should be at least 100, to avoid the drop back of the condensate (Meukam et al., 2004).

2. **Slope of cover and geometry of still angle of inclination.**

The transparent cover of a solar still should be inclined at an angle (β) to the horizontal plane. It is reported that the optimum value of is 100 which just enables the distillate to flow downwards on the inner surface of the cover without dropping back into the basin (Garg & Mann, 1976). So, >100 is sometimes used depending on the latitude (ϕ) of the site (Nafey, et al., 2000). Generally, β = ϕ -100 for summer season (ϕ > 10), β= ϕ for annual performance and β= ϕ +100 for winter season (Samee et al., 2007). Cover inclination of 150 is found to be the best. This may be due to several reasons such as the area allocated to condensation is increased which allows better exchange of heat between the cover and the ambient air. In addition, the condensed water drops on the inner surface of the glass to the channel without falling to the basin, because of higher gradient of the glass inner surface (Samee et al., 2007).

3. **Depth of water in still.**

The performance of a still is considerably affected by the depth of the water in the still. When the level of the water in the still is low, it has a lower thermal capacity and this increases the rate of evaporation and thus higher output. Therefore the lower the water levels the higher the output (Kabeel & ElAgouz, 2011; Tiwari & Tiwari, 2007). When there is low solar energy available in the earlier times of the day, water depth becomes important as you need to heat water quickly to produce fresh water. Solar stills with a water depth of 0.02 m resulted to have the highest annual yield (Kabeel & ElAgouz, 2011; Tiwari &Tiwari, 2007).

4. **Materials for cover.**

The preferred material for the top cover is glass with a thickness of 3 mm (Kabeel & El-Agouz, 2011). Glass has a higher solar transmittance and a longer lifetime compared to plastic, which is advised to be used for the short-term use only (Murugavel et al., 2008). At the same time, glass is more expensive and fragile. The window glass has hardness of 6.5 in Mohs scale of mineral hardness (Dieter, 1989).

DESIGN AND FABRICATION PROCESSES OF DOUBLE SLOPE SOLAR STILL:

A conventional solar still consists of the following basic components namely basin, support structures, glazing, a distillate trough (channel), and insulation. In addition to these, other components may include sealants, piping and valves, tank for storage, an external cover to protect the other components from the weather and a reflector to concentrate sunlight (Gordes, 1985).

Solar still design, the water depth, black dye injection, reduction of the side/bottom heat losses and operational techniques are considered to affect the output of solar stills (Al-ayek & Badran, 2004; Fath, 1998; Tiwari et al., 2003).

In order to build an efficient solar still certain requirements should be met such as to be easily built with locally available materials, light in weight in order to handle and transport easily, should not contaminate the collected fresh water, meet the civil and structural engineering standards and be affordable. The designed solar still should not require any other power source except solar energy and be strong enough to withstand prevailing wind conditions.

A solar still efficiency ranges between 30 – 60 %, depending on materials and design with an effective life span of 10 to 20 years (Twidell & Weir, 2006; Badran & Abu- Khader, 2007).

1. **Distance from the water surface to glass cover.**

A glass cover that is not more than 5 to 7cm from the water surface will allow the still to operate efficiently. Conversely, as glass-to-water distance increases, heat loss due to convection becomes greater, causing the still's efficiency to drop. Some important stills have been built following the low slope design concept for the glass cover, yet using a short, steeply sloping piece of the glass at the rear (Connor, 1980).

2. **Aspect ratio (R).**

Capture of solar energy is also affected by the ratio of the length to width of the still base (R). Effective insolation increased with R but the increase was insignificant for values of R>2.0 for both the double sloped solar still and single sloped solar still at a low latitude (Madhlopa & Clarke, 2011).

3. **Absorbing materials.**

Various approaches for increasing the basin absorptivity have been tested and found effective in increasing the daily yield of a solar still. These include the use of charcoal (Naim; et al., 2003), black and violet dyes, which were found to be more effective than other dyes (Valsaraj, 2002).

4. **Absorbing Area.**

The rate of evaporation of water in the solar still (solar still water output) is directly proportional to the surface area of water and efficiency of the still (Velmurugan et al., 2008; Twidell & Weir, 2006; Badran & Abu-Khader, 2007)). The relationship is shown in equation 2. The productivity increases with the increase in the exposure area of the water. The inner surface of the basin is usually blackened to increase the efficiency of the system by absorbing more of the incident solar radiation (Tiwari et al., 2003).

5. **Cooling of cover.**

Water flow over the still cover at a very low rate has been shown to increase the still output and film cooling parameters such as increasing wind velocity may increase efficiency by 2 0 % (Ayoub & Malaeb ,2012). The convective heat transfer coefficient also increases with wind velocity, leading to a decrease in the cover temperature and hence increases in the overall yield (Sarkar et al., 2008). The productivity of solar still increases with wind speed up to a certain value between 8m/s and 10 m/s for winter and summer conditions, respectively (El-Sebaii, 2007). This value was independent of the still shape and brine heat capacity; the wind was more effective in summer and for higher water masses. Similarly, Fath and Ghazy, (2002), reported that increasing the air flow rate up to 0.5 m3/s increased productivity to almost double with no further improvement obtained with air flowing beyond this rate. On the other hand, Fath and Hosny, (2002), found that glass cover cooling by wet cloth for 1-, 2-, and 6-hour intervals had no effect on productivity and that continuous cooling is needed to release a significant amount of condensation energy.

6. **Depth of brine.**

Studies conducted on the effect of water depth in stills have shown that the highest outputs and efficiencies occur at lower depths of 0.02 m (Tiwari & Tiwari, 2007).

WATER QUALITY TESTS:

Sea water which has an average salinity of 35 ppt not only cause bad taste but it also creates stomach problems and laxatives effects (Sukhatme, 1987). The salt contents should not be above the advised mineralogical quantities shown in table 1. Solar still not only achieve the desired limit of TDS of 500 ppm but it also removes pathogens, nitrates, iron, chlorides and toxic heavy metals like lead, arsenic, cadmium and mercury completely (Al-Hayek & Badran, 2004; Zein & Al-Dallal, 1984). the process also proved to be effective in the destruction of microbiological organisms present in the feed water (Al –Hayek & Badran, 2004). The distillate is thus high purity water. The advised mineralogical quantities are shown in table 1.

Table 1: Advised mineralogical quantities (WHO, 2004).

	total dissolved solids (mg/l)	bicarbonates ions (mg/l)	calcium (mg/l)	magnesium (mg/l)	hardness (mmol/l)	alkalinity (meq/l)
Minimum	100	30	20	10		
Optimum	250-500		40-80	20-30	2-4	
Maximum						6.5

PARAMETER THAT CAN BE MEASURED IN DESIGNED AND FABRICATED SOLAR STILL:

The intensity of solar energy falling on the still is one of the most important parameter affecting production (Ray et al., 2011). The output of a solar still has been measured to be on average 2-5 l/d/m2 (Murugavel et al., 2008; Kabeel & El-Agouz, 2011). The productivity of solar stills is affected by meteorological parameters like solar radiation, sky temperature, wind velocity and ambient temperature (Kabeel & El-Agouz, 2011; Tiwari et al., 2003; Garg & Mann, 1976). Other conditions include geographical location, time of the year, particular solar still design and construction material used, brine depth, water temperature, and other site-specific factors.

ECONOMIC ANALYSIS OF THE DESIGNED AND FABRICATED DOUBLE SLOPED SOLAR STILL:

Many factors affect the cost of distillate obtained from a solar desalination unit. Both capital and running costs are influenced by unit size, site location, feed water properties, product water quality, qualified staff availability, etc. The main economic advantage of solar desalination is that it does not require much infrastructure, and it is simple to locally design, install, operate and maintain. The better economic return on the investment depends on the production cost of the distilled water and its applicability (Fath et al., 2003; Kumar & Tiwari 2004; Govind & Tiwari, 1984).

The life cycle cost analysis should be done in order to make economic viability comparison with other designed and fabricated double solar stills for economic analysis (Kudish et al., 1986; Tiwari, 2011; Garg & Prakash, 2000; Solanki et al., 2009).

The CRF (capital recovery factor), the FAC (fixed annual cost), the SFF (sinking fund factor), the ASV (annual salvage value), average annual productivity (M) and AC (annual cost) are the main calculation parameters used in the cost analysis of the desalination unit.

The AMC of the solar still required are regular filling of brackish water, collecting the distilled water, cleaning of the glass cover and removal of salt deposited (scaling). As the system life passes on, the maintenance on it also increases. Finally, the CPL (cost of distilled water per litre) can be calculated by dividing the annual cost of the system (AC) by annual yield of solar still (M).

Hence the first annual cost (FAC)

FAC =CRFXP ……………………………………………….…….**Equation (4)**

Annual Salvage Value:

The sinking fund factor (SFF) for a system is given by:

$$SFF = \frac{i}{(1+i)^n - 1}$$ ………………………………………………… **Equation (5)**

Therefore, if the salvage value of the system is S then, annual salvage value (ASV)

ASV= (SFF) XS ……………………….…………………………**Equation (6)**

S =0.2 P (assuming 20% of present value as salvage value; no reuse of salvage materials) Further, the system requires some maintenance and it is a varying quantity, therefore the annual maintenance cost should also be considered.

AMC= 0.15FAC ……………………………………….…………**Equation (7)**

(Assuming 15% cost of fixed annual cost

Annual Cost/m = (First annual cost + annual maintenance cost –annual salvage value)

Annual yield = daily output yield (l) x365 days

Annual cost/L (CPL) = [Annual first cost/ Annual yield]

Assuming the reuse of various components even after the useful life of the system is over; the salvage value can be estimated to be 35% of the initial cost, useful life 10 years, interest rate 12% and maintenance cost as 15% of the annual first cost. Where P is the present capital cost of desalination system; i is the interest per year, which is assumed as 12%; n is the number of life years, which is assumed as 10 years in most analysis. Solar stills represent a low-cost technology with low-cost maintenance, which can be carried out by unskilled manpower (Tiwari et al., 2003).

METHODOLOGY:

Solar distillation is one of the most available method for salt water distillation and for run that process sun light is one of the several form of heat energy that can be used to run that process. The purpose behind the solar still is very simple; salt water inside a basin which is painted black enclosed in an air tight area formed by a glass cover is heated up and evaporated due to solar radiation that passes through the glass cover consequently vapour is directed on the glass and condensed in drinkable water as it comes in contact with inside surface of the cover.

Evaporation occurs when molecules of water obtain enough kinetic energy on the surface of the water to change its state from liquids to vapour. Water vapour adds the evaporated molecules between the glass and water and makes a higher temperature difference. This temperature difference affects the water vapours temperature between the water and the glass which creates natural convection. A higher temperature difference give support more convection. When vapours directed on the glass cover it will condense due to loss in kinetic energy which is required to be in the vapour state. Glass is tilted at 150 and condensed water flows down and collected in the bottle. The most important drawback of solar still is that its productivity is very low and it also needed large area. Since productivity rate of solar still depends on solar radiation comes from sun.

Figure 3: The view of double slope solar still can be seen in figure.

SPECIFICATIONS OF DOUBLE SLOPE SOLAR STILL:

Length in ft.	6 ft.
Width	6 ft.
Inclination of cover	15^0 Both sides
Area of glass cover	1.65 m^2 both sides
Area of absorber plate	1.59 m^2 both sides
Thickness of glass	5 mm
Water depth	2 cm

CALCULATION OF EFFICINECY OF SOLAR STILL TAKING SAMPLE SET OF DATA (WITH INSULATION)

DATE: 20 JUNE 2019

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	0.70	37	49	48	51	57	35.23

Calculations:

Latitude ϕ = 28.58

No of days n' = 171

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

$\omega_s = \cos^{-1}$ [-tan $(\emptyset - \beta)$.tanδ]

$\omega_s = \cos^{-1}$ [-tan (28.58-`15).tan23.44]

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

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

$$= \frac{24 \times 1.367 \times 3600}{\prod}\left[1 + 0.033\cos\frac{360 \times 171}{365}\right](1.674 \times \sin 28.58.\sin(23.44) + \cos 28.58.\cos(23.44).\sin 95.98)$$

H_o = 40654.50 kJ/m^2-hr

Or H_o =11.299 kW/m^2-hr

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

Where a = 0.25, b = 0.57

Hg = (11.299 x (0.25+ 0.57) x 10)/12

Hg = 6.349KW/m^2 hr

$$\left(\frac{\overline{H}_d}{\overline{H}_g}\right) = 1.411 - 1.696\left(\frac{H_g}{\overline{H}_o}\right)$$

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

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

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

$$I_o = 1.367 \times 3600\left[1 + 0.033\cos\frac{360 \times 171}{365}\right](\sin 28.58.\sin(23.44) + \cos 28.58.\cos(23.44).\cos(-7.5)) \quad I_o =$$

4700.58 kJ/m^2-hr

= 1.305kW/m^2-hr

For Global hourly radiation:-

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

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

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

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

I_d =1.3.5x 2.896/ 11.299

I_d = 0.334kW/m^2-hr

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

$$r_b = \frac{\sin(23.44)\sin(28.58-15)+\cos(23.44).\cos(-7.5).\cos(28.58-15)}{sin28.58.\sin(23.44)+cos28.58.\cos(23.44).\cos(-7.5)} = 0.987$$

r_b= 0.987

I_b = I_g - I_d

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

So, total tilted surface radiation

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

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

I_t = 0.791kW/m^2-hr

$$\eta_a = \frac{0.70 \times 2368}{3600 \times 0.791 \times 1.65} \times 100$$

= 35.23%

DISTILLATE PRODUCED ON HOURLY BASIS WITH INSULATION AND BLACK DYE:

CALCULATION OF EFFICINECY OF SOLAR STILL TAKING SAMPLE SET OF DATA (WITH INSULATION AND WITH BLACK DYE)

Date: 10 July, 2019

Time in hours	Product from 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 temperature (t_b)	
12:00pm-13:00pm	0.85	39	50	49	53	59	39.40

Latitude ϕ = 28.58

No of days n' = 191

Declination $$(\delta) = 23.45 \sin\left[\frac{360(284+191)}{365}\right]$$

δ = 22.23^0

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

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

$\omega_s = \cos^{-1}[-\tan(28.58-15).\tan 22.23]$

ω_s = 95.6520

ω_s =1.668 radian

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

=2/15 x 95.652

$S_{\max}$ = 12.75hours.

Let S= 7 hours.

Now

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

$$H_o = \frac{24 \times 1.367 \times 3600}{\Pi}\left[1 + 0.033\cos\frac{360 \times 191}{365}\right](1.668 \times \sin 28.58.\sin(22.23) + \cos 28.58.\cos(22.23).\sin 95.652)$$

H_o =40665.002

Or H_o =11.29 kW/m^2-hr

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

Where a = 0.25, b = 0.5

Hg = 6.35 KW/m^2 hr

$$\left(\frac{\overline{H}_d}{\overline{H}_g}\right) = 1.411 - 1.696\left(\frac{H_g}{\overline{H}_o}\right)$$

$$= 1.411 - 1.696\left[\frac{6.35}{11.29}\right]$$

H_d = 2.9 0KW/m^2 –hr

$$r_d = \frac{1+\cos\beta}{2} = 0.89$$

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

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

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

$$I_o = 1.367 \times 3600\left[1 + 0.033\cos\frac{360 \times 191}{365}\right](\sin 28.58.\sin(22.23) + \cos 28.58.\cos(22.23).\cos(-7.5)) \quad =4700.37$$

kJ/m^2-hr

I_0 = 1.3056kW/m^2-hr

For Global hourly radiation:-

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

Where

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

By substituting ω_s =95.652 in above equations we get

$a_1 = 0.701$ And $b_1 = 0.389$

I_g / 6.49 = 1.305/11.29 (.701 + .389.cos-7.5)

I_g = 0.797kW/m^2-hr

Now, For hourly diffuse radiation

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

I_d =1.305x2.90/ 11.29

I_d = 0.335kW/m^2-hr

$$r_b = \left[\frac{\sin\delta.\sin(\emptyset-\beta)+\cos\delta.\cos\omega.\cos(\emptyset-\beta)}{\sin\emptyset.\sin\delta+\cos\emptyset.\cos\delta.\cos\omega}\right]$$

$$r_b = \left[\frac{\sin(22.23)\times\sin(28.58-15)+\cos(22.23)\times\cos(-7.5)\times\cos(28.58-15)}{\sin 28.58\times\sin(22.23)+\cos 28.58\times\cos(22.23)\times\cos(-7.5)}\right] = 1.12$$

$r_b = 1.051$

$I_b = I_g - I_d$

I_b =0.797-0.335=0.462 kW/m^2-hr

So, total tilted surface radiation (I_t) = $I_b.r_b+I_d.r_d+I_g.r_r$

I_t=0.462 × 1.051+ 0.335×0.98+0.797×0.017

I_t= 0.86 kw/m^2-hr

$$\eta_a = \frac{0.85\times 2368}{3600\times 0.86\times 1.65}\times 100$$

= 39.40%

RESULTS AND DISCUSSION

Position of solar still is fixed exact horizontal and orientation as East- West. Sun rises from East and gradually moves towards West and always follows same cycle each day irrespective of season like winter or summer.

It is clear from the Fig.4 and table 3. That as Sun go up; temperatures of different components of still keep rising up to around 12 noon to 1pm and then start decreasing in almost a uniform trend. Table represents temperatures of different components minimum and maximum temperature ranges from 25 °C to 60 °C.

As the bottom temperature goes up, evaporation rate of water from the upper surface of water increases and also, as time passes and glass cover temperature decreases at around 1-2 pm, temperature difference between glass cover (as it decreases with decrease in ambient air temperature), and water upper surface (it still maintains a higher temperature for some time as bottom higher temperature decreases, relatively at a lower rate). This increment in temperature difference automatically sets a pressure difference at the two sides and this situation favours for better evaporation rate and, because glass cover comes down to lower temperatures due to direct contact of ambient air, evaporated vapour condenses rapidly. It is clear from the temperature table that still gives relatively higher production rate at around 12-1 pm.

Table 3: Hourly Temperatures and Distillate Produced with Insulation:

Date: 20thJune 2019

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	46	48	51	15
10-11	0.40	30	51	47	49	54	17
11-12	0.52	36	52	48	52	60	30
12-13	0.70	37	50	49	53	59	35.23
13-14	0.46	35	49	37	51	55	38.5
14-15	0.36	33	41	36	50	52	41
15-16	0.15	31	40	32	47	50	42.5

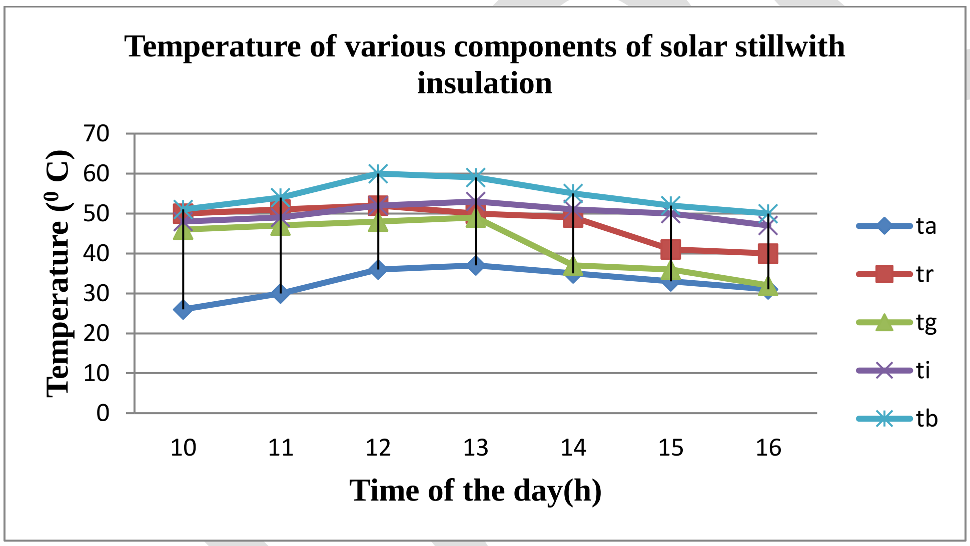

Figure 4: Temp. Of various components of solar still with insulation

Another experiment was carried out for the performance of solar still with inserting black dye at bottom surface and placing fan on still. The Table 4 and Fig 5 represent temperature variation of various components of solar still with time. Due to black bottom surface it absorbed more radiation and having the more temperature at bottom surface.

At the bottom side, due to more absorption bottom temperature and water interface temperature increases to favour the evaporation rate and at glass cover side temperature keep on decreasing rapidly. This situation leads to maintain maximum temperature differential between two sides. This fact is very much clear in the data Table 4. The Data set Fig. 5. Represents that there are two factors which govern the double slope still performance, first evaporation rate basically depends on temperature difference between water surface and glass cover and second evaporation is usually directly proportional to the temperature difference between two sides and the condensation rate will be high as less the glass cover temperature. It is clear from the Fig. 5 that as Sun goes up, temperatures of different components of still keep rising up to around 1 to 2 pm and then start decreasing in almost a uniform trend. Temperature of different components as minimum and maximum temperature ranges from 28°C to 58 °C.

Table 4: Hourly temperatures and distillate produced with insulation with black dye:

Date: 10 th July2019

Time in hours	Product from from still m_w [kg/hr]	Atm. temp (˚C) (t_a)	Temperature (˚C)				η_i (%)
			Moist air temperature (t_r)	Glass Surface temperature (t_g)	Water level interface temperature (t_i)	Bottom temperature (t_b)	
9-10	0.14	27	50	47	48	52	20
10-11	0.42	30	51	48	50	55	18
11-12	0.62	36	53	50	51	61	32
12-13	0.85	39	50	49	53	59	39.40
13-14	0.52	35	48	38	52	56	42.2
14-15	0.46	33	42	37	49	53	44.23
15-16	0.22	32	40	31	47	51	48.1

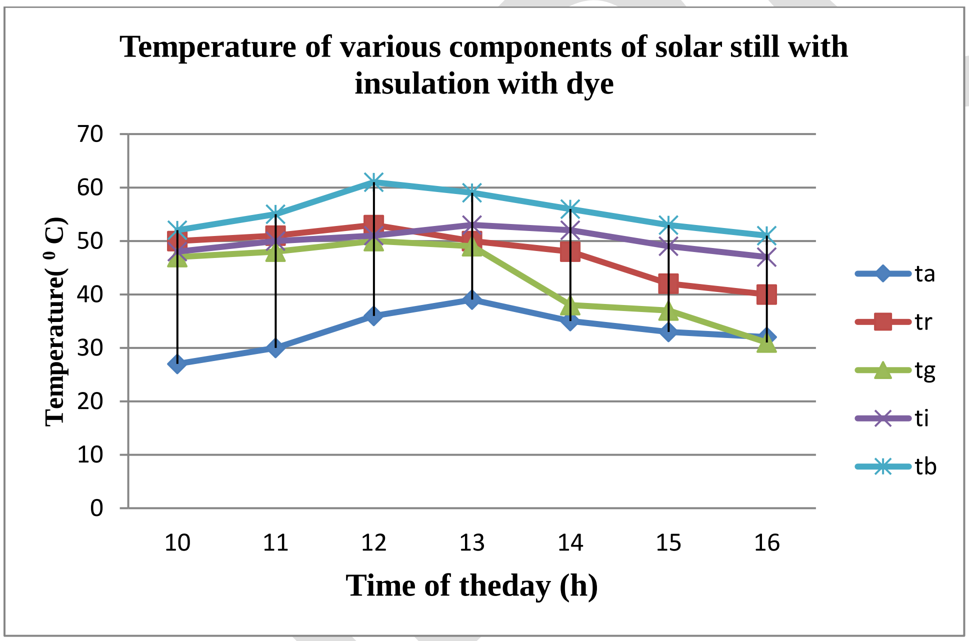

Figure 5: Temp. Of various components of solar still with insulation and dye

Table 5: Distillate produced per hour with insulation and with insulation and dye

Time in hours	Total Product with insulation mwi [kg/hr]	Total Product with insulation and dye mwd [kg/hr]
09-10,	0.14	0.14
10-11,	0.4	0.42
11-12,	0.52	0.62
12-13,	0.7	0.85
13-14	0.46	0.52
14-15	0.36	0.46
15-16	0.15	0.22

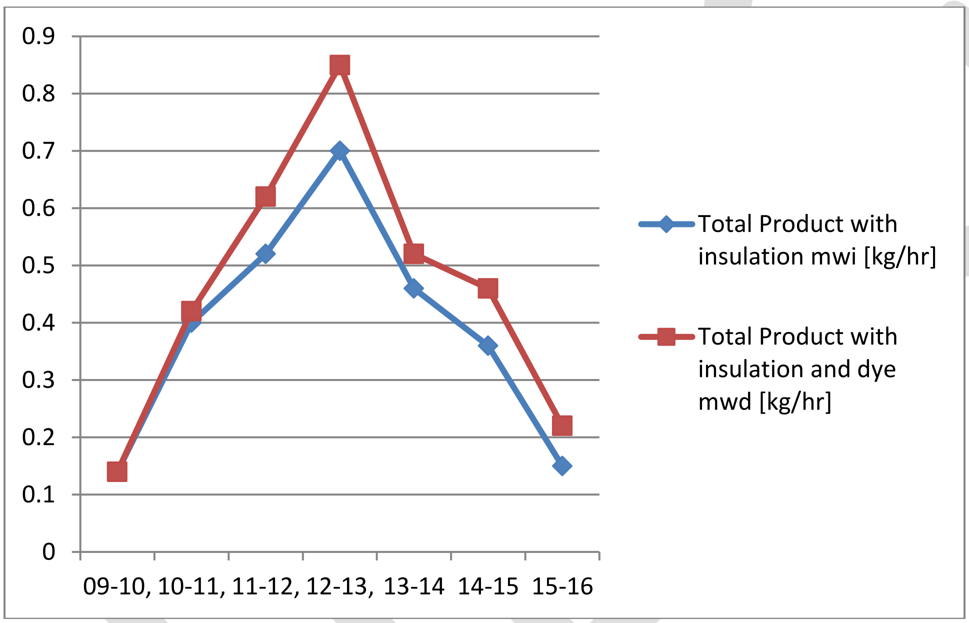

Figure 6: Graph between distillate produced per hour with insulation and with dye.

CONCLUSION

Experiments were run with various modifications i.e. by insulating the still, pouring black dye, so from the results obtained, following conclusions were drawn:

- The distillate output has increased by 15 % by insulation.
- There is further increment of 18% in output by injecting black dye.

The solar still has been fabricated at the home itself and the material was procured from the shops available in local market in Moradabad, whereas thermocouples were purchased from Delhi.

- The amount of transmitted solar energy through the surface of the glass cover of the double slope solar still during the year is estimated for latitude angles between 24° and 31.2°. The main obtained results could be concluded as:
- The mathematical expression for the transmitted solar energy through the surface of the glass cover of the double slope solar still is obtained.
- For single glass solar still, the optimum cover tilt angle that is close or almost equal to the latitude angle with facing to the south direction ($\gamma = 0°$).
- $\beta 1 = \beta 2 = 10°$ are the optimum tilt of the symmetrical double slope solar still without any effect of the orientation due south.

- The optimum tilt of the cover glass of the double slope solar still not necessary to be symmetrical but has values depend on the direction of each surface with respect to the south direction.

The following material was used for fabrication:
Glass cover, Galvanized iron sheet, Bend pipe, Dye, Five thermocouples and Thermopolis sheets.

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