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EFFECT OF GLASS COVER THICKNESS ON THE PERFORMANCE OF STEPPED TYPE SOLAR STILL

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Abstract

The research work carried out so far in the field of solar desalination is related to the single basin type solar still only. The effect of changes in design, climatic and operational parameters on the distillate yield have been studied but limited to the single basin type solar still. The increase in productivity by connecting a flat plate collector which is called as active solar desalination have also been studied but limited to the single basin type solar still. In this work, we have selected a stepped type solar still to improve the performance of single basin type solar still by increasing the production rate of distilled water. The modifications in the design of single basin type solar still are introduced by replacing the flat basin by a stepwise structure. The stepped type solar still selected in this case is having 8 number of steps of size 620 mm(L) x 100 mm(W) and total absorber area equal to 0.5093m2. The characteristic feature of stepped type solar still is that it provides an additional 40% absorber area as compared to the single basin type solar still.

In this work, two number of stepped type solar stills with varying glass cover thickness and other design parameters like depth of water, insulation thickness, condensing cover material, shape of the absorber surface, absorbing material provided over the basin surface, angle of inclination of the still etc. being fixed have been selected for experimentation. The glass cover thickness provided in solar stills A and D was 4 mm and 3.5 mm respectively. After conducting experiments, it has been found that when the glass cover thickness is reduced to 3.5 mm in solar still D, the average daily water production has been found to be 31.13% higher than that of stepped type solar still A. Also an economic analysis was made. The payback period of stepped type solar still with glass cover thickness equal to 4 mm and 3.5 mm is found to be 823 days and 628 days respectively. Thus the stepped solar still with 3.5 mm glass cover thickness gives the returns within the least possible time as compared to the solar still with 4 mm glass cover thickness.

Keywords: **Stepped type solar still, condensing glass cover, distillate yield, distilled water quality.**

Introduction

Water is one of the prime elements responsible for life on earth. It covers three-fourths of the surface of the earth. However, most of the earth's water is found in oceans as salt water, contains too much of salt, cannot be used for drinking, growing crops or most industrial uses. The remaining earth's water supply is fresh water. Most of this is locked up in glaciers and ice caps, mainly at the north and south poles. If the polar ice caps were to melt, the sea level would rise and would flood much of the present land surfaces in the world. The rest of the world's supply of fresh water is found in water bodies such as rivers, streams, lakes, ponds and in the underground. Our drinking water today, far from being pure, contains some two hundred deadly commercial chemicals, toxins and impurities. So there is an important need for clean and pure drinking water. In many coastal areas where sea water is abundant but potable water is not available, solar water distillation is one of the many processes that can be used for purification as well as desalination. Solar still is the widely used solar desalination device. However, the productivity of the solar still is very low. To augment the productivity of the single basin type solar still, several research works has been carried out. These works are summarized as follows.

Experimental Setup

The experimental setup consists of a saline water storage tank and a stepped type solar still mounted on an iron stand as shown in Fig.1. The absorber plate in the still is looking like a stepped type of structure. The absorber plate is made up of galvanized iron sheet of 1mm thickness i.e. 22 gauge. The size of the absorber plate is 620 mm (W) x 808 mm (L). There are totally 8 number of steps in the absorber plate. Each individual step is of 100 mm (W) x 620 mm (L) cross-section and 36 mm height. The stepped type structure of the absorber plate is coated with heat absorbent black dye because it is an established fact that black dye is the best solar radiation absorbing material. The plan and elevation of the stepped type absorber plate is shown in Fig.2.

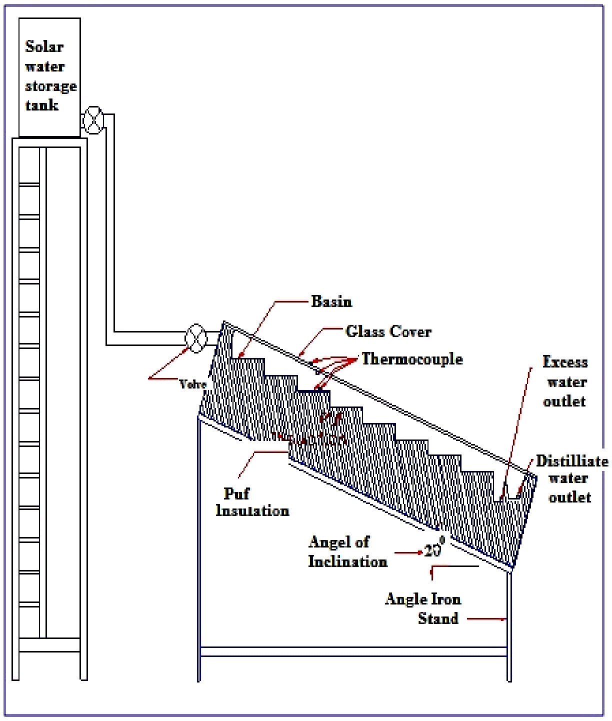

Figure 1. Schematic diagram of the experimental setup

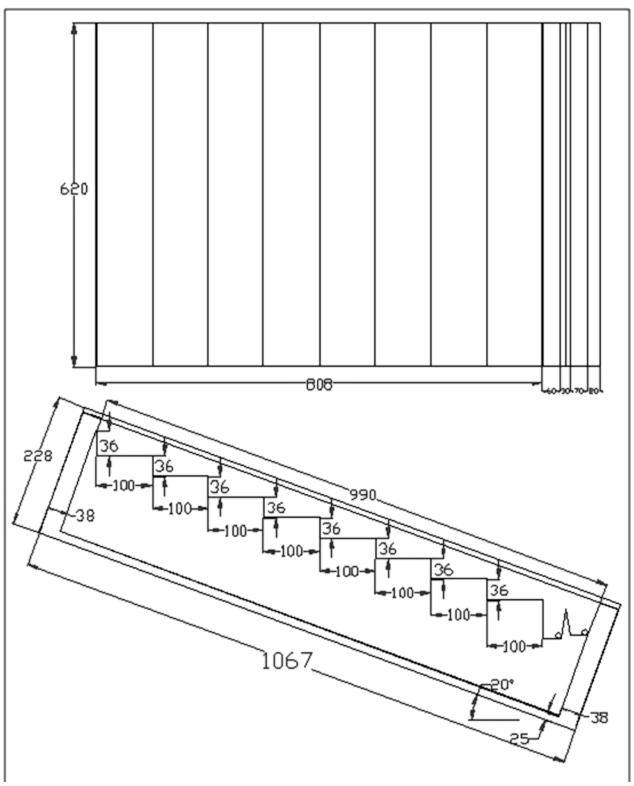

Figure 2. Plan and elevation of the stepped type absorber plate

The absorber plate is placed inside a sheet metal box of size 620 mm (W) x 990 mm (L). The space between the sheet metal box and stepped type absorber plate is filled with poly urethane foam (PUF) to avoid the heat loss from the bottom and sides of the solar still. The cover of the solar still is made up of 4 mm thick simple window glass. The saline water is supplied to the solar still from the saline water storage tank through poly vinyl chloride (PVC) hose pipe. The steps are filled with saline water one after another starting from the top and the excess water comes out from the excess water channel provided at the bottom. The excess water, if any is collected for reuse in the solar still. When solar radiations fall on the glass cover, it gets absorbed by the black absorber plate. Due to this, the water contained in the steps begins to heat up and the moisture content of the air trapped between the water surface and the glass cover increases. When the water absorbs maximum solar radiations equal to the specific heat capacity of its mass, it is saturated and evaporation of water takes place. The basin also radiates energy in the infrared region, which was reflected back into the solar still by the galas cover, trapping the solar energy inside the solar still. The water vapors formed due to the evaporation of water are condensed at the inside of glass cover, as its temperature is less. To ensure that vapors are not lost to the atmosphere, the glass cover is sealed with a rubber gasket using an adhesive of Araldite and Bond-Tite. The condensed water trickles down to the distillate collection trough provided at the bottom and is collected into a glass beaker by using a hose pipe which is mounted at the side of the solar still.

As evaporation of water in the steps takes place, the saline water level in the solar still decreases. To compensate the loss of water, for every half an hour, the makeup water is added to the solar still from the storage tank. A separate hole is also drilled in the sidewall of the still to fix thermocouples to sense the temperatures of water in the basin, absorber plate temperature and inner glass cover temperature. The whole unit is placed on an angle iron stand inclined at an angle of 200equal to the latitude of Buldana to the horizontal. The whole experimental set up was oriented due south as the location lies in the northern hemisphere to receive maximum solar radiation throughout the year.

This experimental setup was designed, installed and tested in the laboratory of Non-conventional Energy Systems, Department of Mechanical Engineering, Rajarshi Shahu College of Engineering, Buldana, India. The experiments were performed during the months of January 2012 to April 2012 when the sky was clear i.e. on sunny days. The average sunshine in Buldana was 5.83 kWh/m2/day during the above said period.

Hourly measurements were made for various temperatures from 9.00am to 5.00pm during the trial period. These temperatures were measured with the aid of J- type iron constantan thermocouples and noted from a digital temperature indicator. Five different thermocouples were installed on the soar still system at different locations. These locations were

(i) bottom of the basin to measure the temperature of absorber plate, Tb (ii) inner surface of the glass cover, Ti (iii) outer surface of the glass cover, To (iv) water temperature in the basin, Tw and (v) ambient temperature, Ta. Thermocouples were integrated with a multi channel digital temperature indicator and a selector switch. The collecting vessel is used for measuring distillate yield and a vane type digital anemometer is used for measuring wind velocity. The alloy combination, polarity and measurement range for the thermocouples is as given in the Table 1.

Table 1. Thermocouples

Sr. No.	Item	Specification
1	Type of thermocouple	J – Type Iron constantan thermocouple
2	Alloy of positive wire	Iron (100% Fe)
3	Alloy of negative wire	Constantan (55% Cu – 45% Ni)
4	Temperature range	0 – 7500C

The hourly weather data, i.e., wind speed was measured with the help of Lutron anemometer. The operating parameters and electrical specifications of anemometer are as given in Table 2.

Table 2. Anemometer

Sr. No.	Item	Specification		
1	Type of anemometer	Vane type digital anemometer		
2	Operating temperature	0 to 50^{0}C		
3	Operating humidity	Less than 80% RH		
4	Measurement in m/s	Range	Resolution	Accuracy
		0.4 – 30 m/s	0.1 m/s	± 2%+0.2m/s)

Stepped type solar still with varying glass covers

The cover of the solar still must transmit solar radiation with minimum amount of absorption and reflection in the solar spectrum. It also acts as resistance to thermal radiation heat transfer from the basin to the atmosphere. The configuration and design parameters of solar stills A and D are as given in Table 3.

Table 3. Design parameters of solar stills A and D

Sr. No.	Type of solar still	Depth of water in mm	Shape of absorber surface	Glass cover thickness in mm
1	A	5	Flat	4
2	D	5	Flat	3.5

Thermal Model

A thermal model has been developed to determine the convective heat transfer for different Grashoff numbers in the solar distillation process. The model is based on simple regression analysis. Based on the experimental data obtained from the rigorous outdoor observations on various configurations of stepped type solar stills for summer climatic conditions, the values of C and n have been calculated. From these values, convective heat transfer coefficient is calculated based on the distillate yield obtained from the experimental observations. The percentage deviation between experimental and theoretical distillate yield is also obtained.

Thermo physical Properties of Water

The thermo physical properties of water have been evaluated by using the following expressions wherein Tv represents the arithmetic mean of the temperatures of evaporation and condensing surfaces and can be expressed as follows:

$$T_v = \frac{(T_w + T_{gi})}{2}$$

$$\rho = \frac{353.44}{(T_v + 273.15)}$$

$$\beta = \frac{1}{(T_v + 273.15)}$$

$$C_{pw} = 999.2 + 0.1434 \times T_v + 1.101 \times T_v^{-2} - 6.75 \times 10^{-8} \times T_v^3$$

$$K_a = 0.0244 + 0.7673 \times 10^{-4} \times T_v$$

$$\mu = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} \times T_v$$

$$h_{fg} = 2324.6\left(\begin{array}{c}1.0727\times10^{3} - 1.0167\times T_v + 1.4087\times10^{-4}\times \\ T_v^2 - 5.1462\times10^{-6}\times T_v^3\end{array}\right)$$

$$P_w = e^{(25.317-5144/T_w)}$$

$$P_{gi} = e^{(25.327-5144/T_{gi})}$$

Internal Heat Transfer Coefficients

Experiments were performed on two different configurations of stepped type solar still during the months of January 2012 to April 2012 for several days, but the measured parameters on a typical day namely, 5th March, 2012 are considered for computations of internal heat transfer coefficients.

The governing equations applied to a stepped type solar still are discussed. Heat transfer occurs across the humid air inside the enclosure of the distillation unit by free convection which is caused by the action of buoyancy force due to density variation in the humid air. Density variation is caused by a temperature gradient in the fluid.

The convective heat transfer rate from water surface to condensing glass cover is given by:

$$q_{c\,w-g} = h_{c\,w-g}(T_w - T_{gi}) \qquad (1)$$

Where,

h_{cw-g} is convective heat transfer coefficient from water surface to condensing glass cover. The convective heat transfer coefficient h_{cw-g} is calculated by using the non-dimensional Nusselt number as shown below:

$$Nu = h_{cw-g}\frac{L_c}{K_a} = C\,(Gr.Pr)^n \qquad (2)$$

In equation (2), non- dimensional numbers Gr and Pr are called Grashoff number and Prandtl numbers respectively. These numbers are expressed as:

$$Gr = \frac{\beta g L_c^3 \rho^2 \Delta T}{\mu^2} \qquad (3)$$

$$Pr = \frac{\mu C_{pw}}{K_a} \qquad (4)$$

Where

$$\Delta T = (T_w - T_{gi}) + \left[\frac{(P_w - P_{gi})(T_w + 273.15)}{268.9\times10^3 - P_w}\right]$$

Variables on right hand side of expressions are the temperature dependent physical properties and are determined as discussed in the previous section.

Equation (2) can be rewritten as,

$$h_{cw-g} = \frac{K_a}{L_c}.C(Gr.Pr)^n$$

$$h_{cw-g} = \frac{K_a}{L_c}.C(Ra)^n \qquad (5)$$

Where Ra = Gr.Pr is the Rayleigh number.

Malik et. al.,1982 [2] have assumed that water vapour obeys the perfect gas equation and have given the expression for evaporative heat transfer rate as:

$$q_{ew-g} = h_{ew-g}(T_w - T_{gi}) \qquad (6)$$

Where, h_{ew-g} is the evaporative heat transfer coefficient between water surface and condensing glass cover and expressed as

$$h_{ew-g} = 0.01623\,.h_{cw-g}.\frac{(P_w - P_{gi})}{(T_w - T_{gi})} \qquad (7)$$

Where

$$P_w = e^{(25.317-5144/T_w)}$$

$$P_{gi} = e^{(25.327-5144/T_{gi})}$$

It is worth mentioning here that only evaporative heat transfer causes and contributes to water distillation

Substituting the value of h_{ew-g} in equation (6) above, we get

$$q_{ew-g} = 0.01623\,.h_{cw-g}.(P_w - P_{gi}) \qquad (8)$$

Substituting the value of h_{cw-g} in the above equation, we get

$$q_{ew-g} = 0.01623\,.\frac{K_a}{L_c}\,.(P_w - P_{gi}).C.(Ra)^n \qquad (9)$$

By knowing the evaporative heat transfer rate; mass of the water distilled can be derived by the following equation:

$$\dot{m}_{ew} = \frac{q_{ew-g}.A_w.t}{h_{fg}} \qquad (10)$$

Substituting the value of q_{ew-g} in the above equation, we get

$$\dot{m}_{ew} = 0.01623\,(P_w - P_{gi})\left(\frac{K_a}{L_c}\right)\frac{1}{h_{fg}}\,C\,(Ra)^n \qquad (11)$$

$$\dot{m}_{ew} = R.C.(Ra)^n \qquad (12)$$

$$\frac{\dot{m}_{ew}}{R} = C\,(Ra)^n \qquad (13)$$

Where,

$$R = 0.01623\,(P_w - P_{gi})\frac{K_a}{L_c}.\frac{1}{h_{fg}}$$

In equation (13), there are two unknown parameters C and n. They are determined by regression analysis using experimental values of distillation yield (mew), saline water temperature in the basin (Tw), glass cover temperature at the inner surface (Tgi).

Equation (13) can be rewritten in the following form:

$$Y = aX^b \qquad (14)$$

Where, $Y = \frac{\dot{m}_{ew}}{R}$; $X = Ra$; $a = C$; $b = n$

Equation (14) can be reduced to a linear equation by taking log on both the sides:

$$ln\,(Y) = ln(a) + b\,ln(X) \qquad (15)$$

OR $\quad Y' = a' + b'X' \qquad (16)$

Where

$$Y' = \ln(Y);\quad a' = 1n(a);\quad b' = b;\quad X' = \ln(X) \tag{17}$$

From equation (17), the values of coefficients a' and b' are calculated using regression analysis. The expressions for a' and b' are given by:

$$b' = \frac{N(\Sigma X'Y') - (\Sigma X')(\Sigma Y')}{N(\Sigma X'^2) - (\Sigma X')^2} \tag{17a}$$

$$a' = \frac{\Sigma Y'}{N} - b'\frac{\Sigma X'}{N} \tag{17b}$$

where N is the number of experimental observations.

Knowing a' and b' from equation (15), the value of C and n can be obtained by the following expressions:

$$C = e^{a'}\ and\ n = b'$$

Once the values of C and n are known, the experimental data are used to obtain the internal heat and mass transfer coefficients for the solar stills. Equation (3) can be used to obtain the convective heat transfer coefficient, h_{cw-g}. Dunkle [1], by using the values of C = 0.075 and n = 1/3, gave following expression for h_{cw-g}, valid for a mean operating temperature range of approximately 500C.

$$h_{cw-g} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273.15)}{268.9\times10^3 - P_w}\right]^{1/3} \tag{18}$$

The internal heat transfer coefficient; heat transfer from water to glass cover inside the solar still is done by three possible ways called evaporation, convection and radiation, Hence total internal heat transfer coefficient of solar still is sum of all three possible ways heat transfer coefficients,

$$h_1 = h_{cw-g} + h_{ew-g} + h_{rw-g} \tag{19}$$

In equation (19), h1 is total heat transfer coefficient and h_{cw-g}, h_{ew-g} and h_{rw-g} are called convective, evaporative and radiative heat transfer coefficients.

The radiative heat transfer coefficient between the water surface and condensing glass cover is given by is given by following equation:

$$h_{rw-g} = \varepsilon_{eff}\,\sigma\left[(T_w + 273)^2 + (T_g + 2732Tw+Tg+546\right. \tag{20}$$

Where, $\sigma = 5.669 \times 10^{-8}\ W/m^2K^4$

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1} \tag{21}$$

Where, εg and εw are emissivities of basin water and glass cover and are given by

$$\varepsilon_w = \varepsilon_g = 0.9$$

Efficiency of Solar Still

Efficiency of solar still [9] is simply defined as the ratio between thermal energy utilized to get distillate water in a period and energy supplied to solar still during the same period. The efficiency of various configurations of the solar still can be calculated by using the following equation,

$$\eta = \frac{\sum m_{ew}.h_{fg}}{\sum I(t).A_b + m_w.C_{pw}.(T_w - T_a)} \times 100 \tag{22}$$

Where m_{ew} is the distillate yield obtained in kg/m^2/day and h_{fg} is the latent heat of vaporization of water in kJ/kg.

Results and Discussion

Variation of basin water temperature for solar stills A and D

The distillate yield is the major factor in determining the performance of a solar still. The efforts of all the researchers working in this area are directed towards obtaining the maximum distillate yield for the given set of conditions. The distillate yield is dependent on two main variables; firstly the basin water temperature and secondly the difference between basin water and inner glass cover temperatures. In this case, solar still A is provided with a glass cover of 4 mm thickness whereas solar still D is provided with a glass cover of 3.5 mm.

Fig.4 shows relation between the time of the day (hrs) and basin water temperature for solar stills A and D on 5th March, 2012. Evaporation of water is also a key factor in determining the performance of a solar still. It occurs due to the thermal energy of the solar still. It depends on glass cover thickness; other parameters being constant. It shows that, the increase in basin water temperature is higher in case of solar still D with 3.5 mm glass cover thickness as compared to the solar still A with 4 mm glass cover thickness.

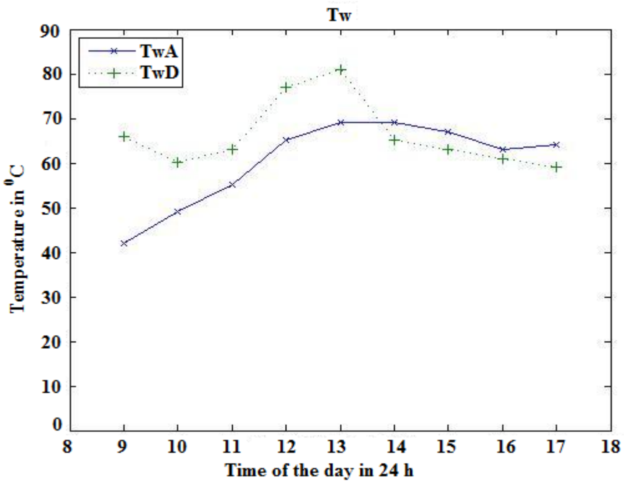

Figure 4. Temperature of water in basin for solar stills A & D

Variation of basin water-inner glass cover temperature difference for solar stills A and D

Fig. 5 shows relation between the time of the day (hrs) and inner glass cover temperature for solar stills A and D on 5th March, 2012. The temperature difference between the basin water and inner glass cover temperature is also another factor in determining the performance of a solar still. It depends on glass cover thickness; other parameters being constant. It shows that, the difference in basin water and inner glass cover temperature is more in case of solar still D with 3.5 mm glass cover thickness as compared to the solar still A with 4 mm glass cover thickness.

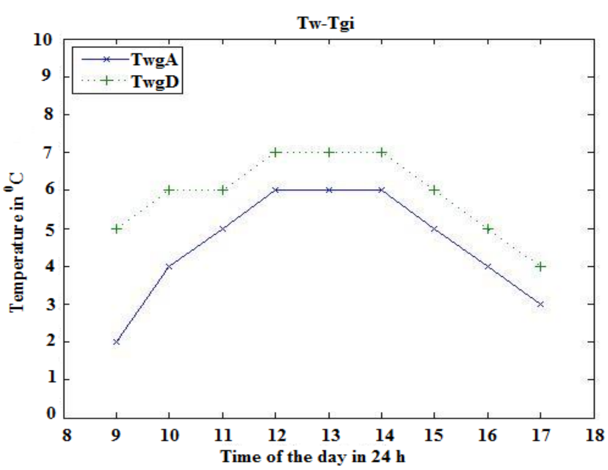

Figure 5. Basin water-inner glass cover temperature difference for solar stills A & D

Variation of distillate yield for solar stills A and D

Fig.6 shows the relation between time of the day (hrs) and distillate yield for solar stills A and D respectively on 5th March, 2012. On a typical day mentioned above, the distillate yield obtained for solar still A and D is observed to be 1060 ml and 1390 ml during the period from 10 am to 5 pm. It shows that, 3.5 mm glass cover thickness of solar still D increases distillate yield as compared with 4 mm glass cover thickness of solar still A. Due to the decrease in glass cover thickness, the distillate yield increased by 330 ml and this is 31.13% higher than of the solar still A.

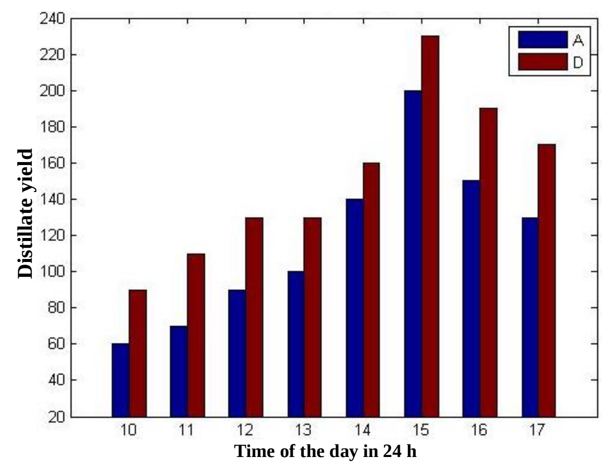

Fig. 6: Distillate yield with time of the day for solar stills A & D

Thermal conductivity of glass cover is low and heat dissipation from the glass cover to the atmosphere is due to natural convection as well as radiation. Hence, overall heat transfer coefficient is very low reducing the heat transfer between glass cover and the environment. Hence part of latent heat of condensation is accumulated in air vapor mixture, this phenomena in thermal science is called as thermal inertia.

Efficiency of Solar Still

The efficiency of the solar stills A and D was calculated using the formula given in section 4.3 and it turned out to be as given in Table 6.1. The solar stills installed in the different parts of the world have efficiencies of the order of 30-40% [4].

Table 4: Still efficiency of solar stills A and D

Solar still	Depth of water in mm	Glass cover thickness in mm	Shape of absorber surface	Efficiency of Solar Still in%
A	5	4	Flat	21.42
D	5	3.5	Flat	28.09

Economic Analysis

The cost of distilled water produced by the stepped type solar still depends upon the following factors.

- The capital cost gets reduced if locally available materials are used.
- As the solar energy is available free of cost, it has no effect on the total cost of the solar still.
- The operation and maintenance cost is almost negligible.

The production rate of distilled water is proportional to the area of the solar still; which means that the cost per liter of water produced is nearly the same regardless of the size of the fabricated still. The payback period of the experimental setup depends on overall cost of fabrication, maintenance cost, operating cost and cost of feed water. The overall fabrication cost is Rs. 8723. It is not necessary to take into account the operation and maintenance cost and the cost of feed water, which is almost negligible.

Table 5. Calculation of payback period

Sr. No.	Item	A	D
1	Overall cost to be considered	Rs. 8723	Rs. 8723
2	Cost per litre of distilled water	Rs. 10	Rs. 10
3	Average productivity of solar still	1.06 litres per day	1.39 litres per day
4	Cost of distilled water produced per day	Rs.10.6	Rs.13.9
5	Payback period of solar still	823 days	628 days

Distilled water quality

Two different water samples from solar stills A and D were tested in the District Public Health Laboratory, Buldana, Government of Maharashtra, India. The distilled water was tested with highly accurate digital instruments having an accuracy of ±l mg/l. The laboratory test results as shown in Table 4 indicate that the quality of water after distillation is well within the desirable limits as prescribed by WHO for Indian specific conditions.

Table 6. Report on chemical examination of water for drinking purposes

Sr. No.	Tests	Sample No.1(A)	Sample No.2(D)	Desirable limits
1	pH	6.9	6.8	6.5-8.5
2	Electrical conductivity, µS/cm	80.4	97.0	750
3	Chloride as Cl, mg/l	10	21	250
4	Total hardness as $CaCO_3$, mg/l	20	22	300
5	Total dissolved solids, ppm	40	50	500
6	Turbidity as NTU	0.03	0.03	-
7	Iron as Fe, mg/l,	0.01	0.01	-
8	Fluoride as F, mg/l	0.21	0.27	-
9	Alkalinity as $CaCO_3$, mg/l	60	40	200
10	Nitrates as NO_3, mg/l	Nil	Nil	50
11	Physical appearance	Clear	Clear	-

Summary and Conclusions

Two numbers of solar stills with different glass cover thicknesses were installed and tested. Solar still A was provided a glass cover with 4 mm thickness and solar still D was provided a glass cover with 3.5 mm thickness. Other parameters like depth of water and shape of absorber surfce were kept constant. It has been observed that the distillate yield of solar still D is 31.13% higher than that of solar still A. Hence, it can be concluded that lesser the glass cover thickness, higher is the distillate yield.

Solar still D was shown to have the highest thermal efficiency of about 28.09%.The laboratory tests indicate that the distillation process has eliminated total dissolved solids and total hardness. This shows that the distillation process is suitable for obtaining potable water as per the prescribed standards. Also, an economic analysis was made. The payback period of the solar still D with 3.5 mm glass cover thickness is the least as compared to the solar still with 4 mm glass cover thickness and it is 628 days.

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