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Full Length Research Paper

Design and development of wick type solar distillation system

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The single basin wick type solar desalination was designed with corrugated galvanized iron sheet of area 1 m^2 as an absorber in between the wick strip for obtaining maximum temperature inside the distiller. This distiller was tested at different inclinations for load and no load test in winter and summer months. The chemical analysis of the distilled water and impure water was carried out. The economic of the present system was studied. The cost of the system was calculated. The system was tested by applying statistical approach to estimate the best method for desalination. The average yield of distilled water from Single Basin Wick Type Solar Desalination Plant (SBWSD) was 2300 ml/m^2/day in winter and 3400 ml/m^2/day in summer at Dapoli, India. Maximum distilled water obtained at an angle 40º48' in winter season. The efficiency of the SBWSD was 47.14% in winter and 56.29% in summer. The benefit cost ratio and pay back period for SBWSD was 1.70 and 6 months, respectively.

Key words: Wick type solar distillation, chemical analysis, economics.

INTRODUCTION

Distillation is a process of converting impure water into pure (distilled) water but it requires large amount of conventional energy. The theoretical minimum energy needed to desalt 1 m^3 of seawater at 25°C is 0.7 kWh. However, as desalination is not a reversible process, about 2 to 7 times this amount of energy is needed at a minimum depending on the desalination method being used. Solar energy is available and free cost and non-extinguishing in nature. Hence, solar energy is the cheapest option for this process which helps to reduce the greenhouse gases in environment. Lot of devices is available to produce distilled water in market. These all types of solar distillation devices are pounding water type which do not produce distilled water more than 2 L/day/m^2 in this region. Comparatively, low cost solar distillation device with producing higher output is needed in this region. By keeping in a view, importance of solar distillation unit, study has been under taken to develop wick type solar distillation unit.

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MATERIALS AND METHODS

Design considerations

The solar collector was designed by considering latitude 17˚45' N and lowest temperature in winter, as 10th of December is 450 W/m^2 for Dapoli, India (Anna and Rangrajan, 1980)

Slope of collector (β)

Optimum slope of collector for winter was calculated using angle of solar declination (δ), number of days, latitude at test site, and angle of incidence from the following equation (Brenidorfer et al., 1985):

$$\delta = 23.45 \sin [0.9863 (284 + n)] \quad (1)$$

where,

n = Number of days.

Slope of collector (β) is calculated by using the following formula:

$$\beta = (\Phi - \delta)$$

where,
Φ = Latitude at test site,
= 17˚45' N

Positive value of β = Collector should be south facing.

Intensity of insolation

Instantaneous insolation on the surface was approximately proportional to the cosine of angle of incidence (θ).

The angle of incidence for insolation falling on south facing roof at midday can be calculated by using following equation (Brenidorfer et al., 1985)

$$\text{Cos } \theta = \text{Sin}\delta \text{ . Sin } \Phi \text{ . Cos}\beta - \text{Sin}\delta \text{ . Cos } \Phi\text{. Sin}\beta\text{. Cosr} + \text{Cos}\delta\text{. Cos } \Phi\text{. Cos}\beta\text{. Cos}\omega + \text{Cos}\delta\text{. Sin } \Phi \text{ Sins Cos}\omega + \text{Cos}\delta\text{. Sin}\beta\text{. Sinr. Sin}\omega \quad (2)$$

where, δ = Angle of incidence; Φ = Latitude of the test; β = Slope of collector, and r = Surface azimuth angle; for structure, this can be considered as its orientation with respect to a north south axis. The angle varies from -180˚ to +180˚; zero is due to south, east is negative and west is positive. The value of r = 0 was used for the present calculation. ω = the hour angle, which is the angular displacement at the sun east or west. It is zero at a solar noon and changes 15˚/h. Morning is negative and afternoon is positive. ω = 0 is used for the present calculation.

The following equation was used to determine the intensity of insolation on collector surface (I_c),

$$I_c = I_g \times \text{Cos}\theta \quad (3)$$

where, I_h = intensity of insolation on horizontal surface, W/m^2; Cosθ = Cosine of angle of incidence (θ) or angle between the beam radiation on surface and normal to surface. For a horizontal surface, since β = 0 and hence, Cos β = 1 and Sin β = 0. Now,

$$\text{Cos } \theta h = \text{Sin } \delta\text{. Sin } \Phi + \text{Cos } \delta\text{. Cos } \Phi\text{. Cos } \omega \quad (4)$$

Hence, level of insolation on sloping surface is calculated as:

$$I_s = I_h \times \text{Cos } \theta/\text{Cos } \theta h \quad (5)$$

where, Cos θh = cosine of angle of beam radiation on horizontal surface.

Details of Single Basin Wick Type Solar Desalination Plant (SBWSD)

Single Basin Wick Type Solar Desalination Plant was fabricated at the central workshop of the College of agricultural Engineering and Technology, Dapoli, India. The pictorials view with different component of SBWSD unit is shown in Figure 1.

The device was consisted of a base frame made up of angle Iron of size 1 inch × 1 inch × 4 mm, which was 1 × 1 m in size and formed the rigid base for the complete unit as shown in Figure 2.

The main frame was also made up of angle Iron of size 1 inch × 1 inch × 3 mm, rested on the base frame and hinged from one side for the angle adjustment. The frame was enclosed with the 18 gauges and 24 gauges galvanized iron, sheets and an insulator was placed in between the two sheets from all sides except from top. The absorber consisted of a corrugated sheet of 24 gauges and of 1 m^2 area, for maximum absorption of incident solar radiations. The still was painted with a blackboard color for attaining higher absorption of incident solar radiations. The still is covered with a glass cover of 5 mm thick plane glass, fitted in aluminum frame having an area of 1 m^2. This glass cover provides cooling effect to inside vapor for condensation.

The system was basically divided into three components as heating chamber, cooling cover and collection unit. Inside the heating chamber, GI pipe was provided for continuous water supply with either pin holes of 1/8th drill. The pipe is connected to a storage tank for continuous water supply.

The jute was used as a wick material, which laid on the absorber with sufficient open area for exposing the black ridge of corrugated absorber. The wick material absorbs the droplets of water from perforated GI pipe and carries this water along the length of the wick material. During this process, the remaining water was collected through the drain outlet and distilled water was collected from opposite side to drain water in a beaker.

The water which was evaporated at higher temperature inside the heating chamber gets condensed on the glass surface. This glass cover was provided with inside barrier for condensed droplets for its collection. Water vapor inside the heating chamber gets condensed in small droplets of liquid due to temperature gradient of inside and outside of glass cover. The angle of the collector with respect to horizontal was changed by an arrangement provided to the device with square pipe and bolts.

Measuring devices

Temperature recorder

The temperature recording instrument consists of a temperature sensor (probe). The electronic data logger ambetronic make with temperature sensor (p type probe) was used to record temperature at different time intervals. The data logger was able to display as well as record any temperature. The instrument was having facility for recording the temperatures automatically at set intervals.

Calibration of thermometer

Probes of data logger were calibrated against an ordinary glass thermometer for two different conditions, including, normal tap water and boiling water. For first condition, the tap water was taken in a beaker and the sensor with ordinary glass thermometer was dipped into water and placed in such a way that sensor and thermometer were at the same elevation without touching to each other and then temperature was noted as indicated by them. Then, the water in the beaker was boiled on the heater and against probe and ordinary thermometer were dipped into the water and placed in such a way that, the sensor and thermometer were at same elevation and temperature were noted as indicated by them.

Thermometers

Calibrated electronic thermometer of temperature range from 0 to 100°C was used for the measurement of maximum and minimum temperature.

Solar insolometer

Solar insolometer manufactured by Surya Systems, Ahemadabad was a very small and handy instrument, which was used for the measurements of solar intensity at a point. It has a sensor which senses the solar radiation falling over its surface and displayed the insolation in W/m^2. This sensor is always kept in horizontal position for accurate readings. A 9 V DC battery was used to operate it. The corresponding value of solar radiation in W/m^2 is observed in liquid crystal display screen (1 lux = 8.523 × 10^{-3}W/m^2).

Anemometer

The anemometer is an instrument was used for calculating the

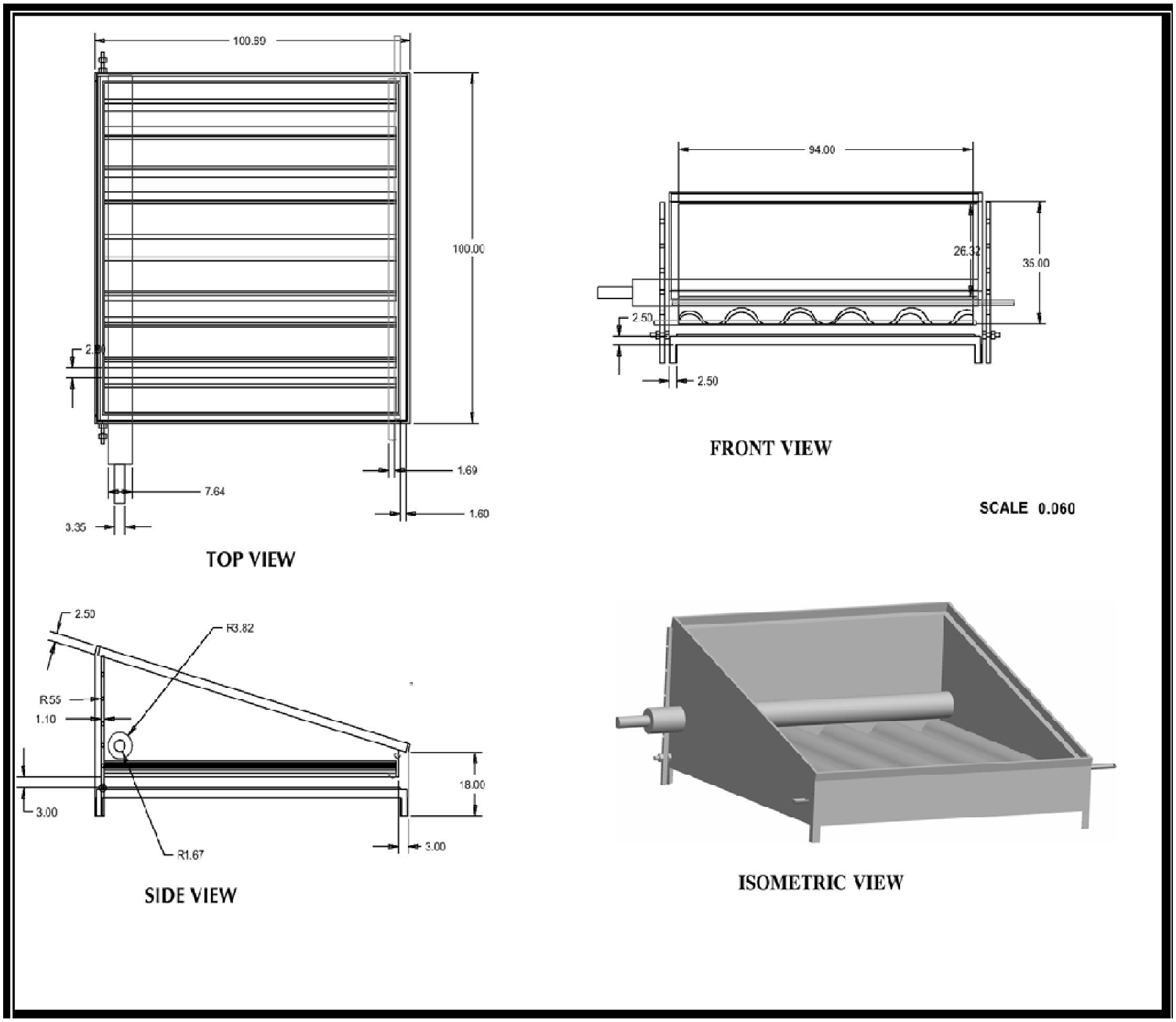

Figure 1. Constructional detail of SBWSD.

prevailing wind velocity in SI units. It has a probe having fan which is kept perpendicular to the prevailing wind direction and the velocity is displayed on the screen.

Relative humidity meter

The RH meter was used for the measurement of the relative humidity of the surrounding. It required 9 V DC supply and a probe to keep it in the surrounding. The humidity was displayed on the screen of the meter in percentage and the range is from 0 to 100%.

Digital Total Dissolve Solid (TDS) meter and pH meter

This meter directly indicates the total dissolved solids in water. Glass electrode was dipped in distilled water and the digital reading of TDS meter was set at zero. Then the sample was tested and direct reading was obtained in ppm.

The pH meter consists of an electrode, which is dipped in distilled water for calibration to set a reading of 7.0. Hence, afterwards the direct readings of the pH meter could be measured for sample.

Performance evaluation of SBWSD

In order to evaluate the performance of SBWSD, ambient temperature, ambient relative humidity, wind speed, inside temperature, inside relative humidity, solar insolation and distillation collected were measured at an interval of one hour during day time from 8.00 A.M. to 6.00 P.M. The system was evaluated with no load and with load (Kothari and Sengar, 2007).

No load test

SBWSD was evaluated without water inside the heating chamber (Lawrence et.al., 1990). In no load test, solar intensity, ambient

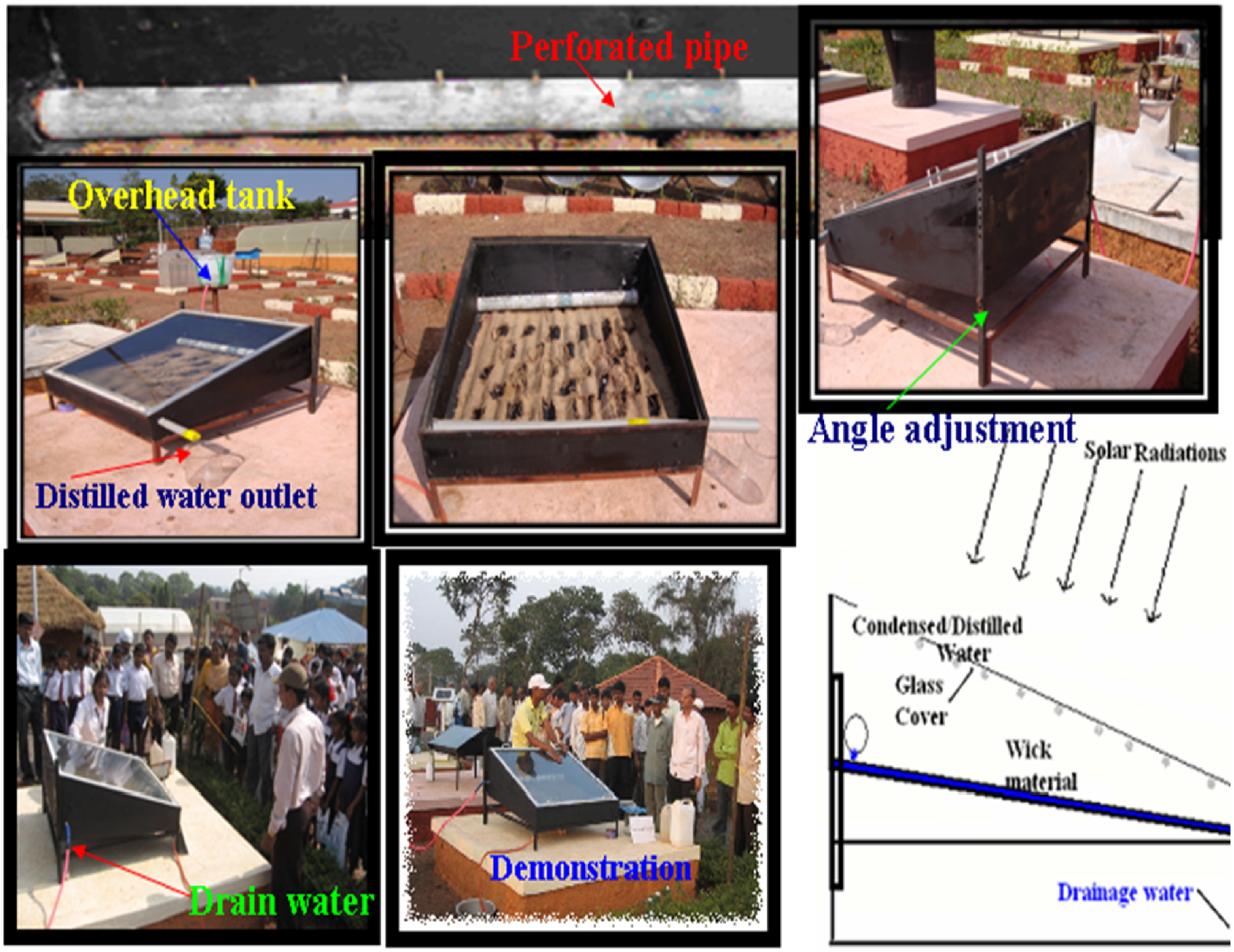

Figure 2. Single basin wick type solar distillation system.

temperature, ambient relative humidity, wind speed, inside temperature, inside relative humidity of heating chamber were measured for studying the thermal profile inside the heating chamber.

Load test

SBWSD was tested with water as pounding, on wick and at various angle adjustments. Total distilled obtained water was measured with corresponding solar intensity, ambient temperature, ambient relative humidity, wind speed, inside temperature, inside relative humidity. Hourly distilled water as well as cumulative distillation rate was studied in this test.

Distillation efficiency

$$ή_{dist} = \frac{Qe}{Qt} \quad \text{(Kumar and Tiwari, 1996)} \quad (6)$$

where, Q_e = Heat required, kWh, and Q_t = Heat available, kW-hr

Chemical analysis

Chemical analysis of impure (tap and saline) and pure (distilled) water which were used for the study was carried out for pH, electrical conductivity (EC), TDS (Mg^{2+}, Ca^{2+}, Na^{+} ions etc.)

Economic analysis

For the success and commercialization of any new technology, it was essential to know whether the technology was economically viable or not. Therefore, an attempt will be made for estimation of economic study of the SBWSD. Different economic studies indicates like net present worth (NPW), internal rate of returns (IRR), benefit cost ratio (B/C), payback period (PBP) were used for the economic analysis of solar system under this study (Sinha and Kumar, 1993).

Net present worth (NPW)

The present value of the future returns was calculated through the use of discounting. Discounting was essentially a technique by

Table 1. Design parameter for SBWSD.

Parameter	Design
Solar declination angle (δ)	δ = -23˚3'
Slope of collector (β)	β = 40°48'
Solar intensity horizontal surface of collector (Ic)	Ic = 450 W/m^2
Insolation on sloping surface (Is)	Is = 594.5 W/m^2
No. of days for 10 December	n = 344
Latitude of the site	Φ = 17°45'N
Surface azimuth angle	r = 0
hour angle	ω = 0

which future benefits and cost streams can be reduced to their present worth. The process of finding the present worth of a future value is called discounting. The discounting rate is the interest rate assumed for discounting.

An agricultural project returns the same benefit for several years and we need to know the present worth of that future income stream to know how much it was justified in investing today to receive that income stream. In SBWSD, the life of SBWSD structure was different from the life of glass cover. Therefore, cost involved in changing the glass cover after its useful life was considered. After deducting capital investment from gross benefit, what is left over is a residual that is available to recover the investment made in the project. The residual is the net benefit stream.

The most straightforward discounted cash flow measure of project worth is the net present worth (NPW). The net present worth may be computed by subtracting the total discounted present worth of the cost stream from that of the benefit stream.

The mathematical equation for net present worth can be written as:

$$\text{NPW} = \sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t} \tag{7}$$

Internal rate of return (IRR)

Another way of using the incremental net benefit stream or incremental cash flow for measuring the worth of a project is to find the discount rate that makes the net present worth of the incremental net benefit stream or incremental cash flow equal to zero. This discount rate is called the internal rate of return. It is the maximum interest that a project could pay for the resources used if the project is to recover its investment and operating costs and still break even. It is the rate of return on capital outstanding per period while it is invested in the project. The internal rate of return is a very useful measure of project worth.

Internal rate of return is the discount rate i such that:

$$\sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t} = 0 \tag{8}$$

Benefit cost ratio (BCR)

This ratio was obtained when the present worth of the benefit stream was divided by the present worth of the cost stream. The formal selection criterion for the benefit-cost ratio for measure of project worth was to accept projects for a benefit-cost ratio of 1 or greater.

The mathematical benefit-cost ratio can be expressed as:

$$\text{Benefit-cost ratio} = \frac{\sum_{t=1}^{t=n} \frac{Bt}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{Ct}{(1+i)^t}} \tag{9}$$

where, C_t = Cost in each year; B_t = Benefit in each year; t = 1, 2, 3................n, and i = discount rate

Payback period (PBP)

The payback period is the length of time from the beginning of the project until the net value of the incremental production stream reaches the total amount of the capital investment. It shows the length of time between cumulative net cash outflow recovered in the form of yearly net cash inflows.

RESULTS AND DISCUSSION

Different parameters were design as summarize in Table 1. The experimental data of the plant with no load and with load tests was determined with environmental data such as ambient temperature, ambient relative humidity, w δ = - 23˚3' wind speed, inside temperature, inside relative humidity, solar insolation and the cumulative distillation.

Performance evaluation

SBWSD was evaluated for winter and summer seasons with no load and load test at 10, 20, 30 and 40° angle by using wick material. The system was also tested for impounding type performance for comparison with single and double slope distillation unit.

In no load test in winter season, maximum temperature was obtained at 1 PM, where solar intensity was 503 W/m^2, inside temperature was 91°C, ambient temperature was 31°C and outside relative humidity was 45.6%.

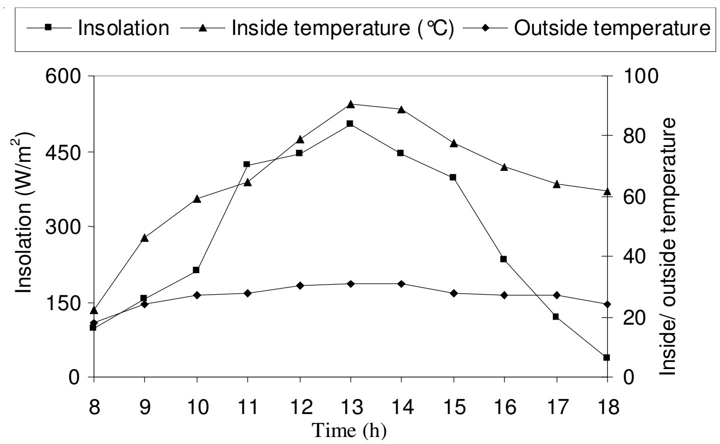

Figure 3. Performance of SBWSD no load tests in winter.

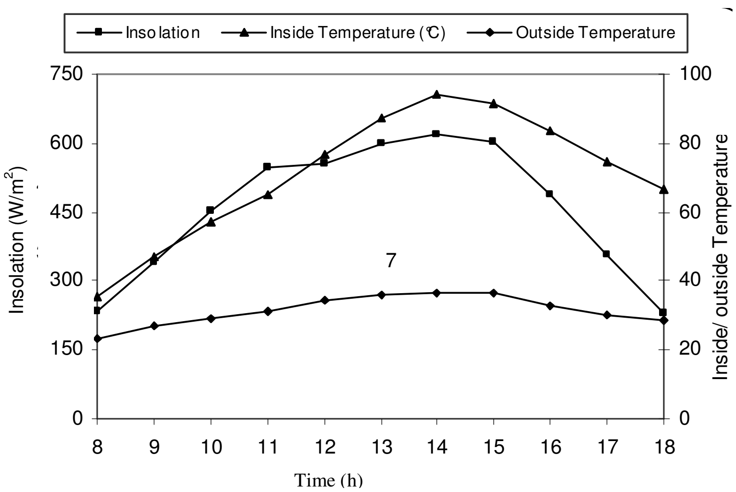

Figure 4. Performance of SBWSD no load tests in summer.

The trend obtained in no load test during performance of distillation unit. It was observed from Figure 3 shows that as inside temperature increases, inside relative humidity decreases and vice versa. It was also observed that the temperature inside the distillation unit increases with outside solar radiation.

In no load test in summer season, maximum temperature was obtained at 2 PM., where solar intensity was 618 W/m^2, inside temperature was 94℃, ambient temperature was 36.5℃ and outside relative humidity was 34.5%. The trend obtained in no load test during performance of bare distillation unit. It was observed from Figure 4 that as inside temperature increases, inside relative humidity decreases and vice versa. It was also observed that the temperature inside the distillation unit increases with outside solar radiation.

The distilled water obtained from SBWSD at different method with various angle is summarize in Table 2. It was observed that cumulative distilled water was increase in the yield as the angle of inclination of the collector was increased from 10 to 40°in winter. Reason behind the increasing distillation rate with increasing angle due to incoming radiation intercepted on the collector from lower side in winter and also in winter season, the solar declination angle is more as per the design calculations. In summer season, it was observed as decreasing the angle, yield of SBWSD was increased due to the solar radiation intercepted on collector area from upper side and also the solar declination is minimal in summer season. Maximum yield obtained in summer season from SBWSD was 3400 ml at the lowest angle, that is, 10°.

The average distilled water in 24 h produced from SBWSD in November-and December 2008 was 2000 and 2300 ml/m^2/day, respectively comparing to Single and Double Slope solar distillation plant available in market was only 1000- and 1200 ml/m^2/day for Dapoli, India and the distilled water produced in 24 h from SBWSD in the month of April and May 2009 was 2700 and 3300 l/ m^2/day, respectively for Dapoli, India whereas plants

Table 2. Performance of SBWSD at various angles with wick material.

Type	Distilled water obtained	
	Winter	Summer
Impounding	1610	1900
Wick type 10°	1810	3400
Wick type 20°	2050	3200
Wick type 30°	2150	2750
Wick type 40°	2300	2550

Table 3. Chemical analysis of impure and pure water samples.

Chemical property	Tap water	Distilled tap water	Saline water	Distilled saline water
pH	7.63	7.0	9.3	7.02
EC (dS/m) at 31.6°C	160	70	72.4×10^6	90.59
TDS (Hardness, ppm)	550	20	35780	79
Na^+ (ppm)	3.6	0.1	1066	0.1
K^+ (ppm)	1.2	1.0	228.9	1.1
Ca^{2+} (me/L)	0.00092	0.00040	_	0.00048
Mg^{2+} + Ca^{2+} (me/L)	0.0018	0.00072	_	0.00090
Mg^{2+} (me/L)	0.00088	0.00032	_	0.00042
CO_3^{2-} (me/L)	0.6	0	3.4	0
HCO_3^- (me/L)	0.2	0.14	0.7	0.3
Cl^- (me/L)	1.5	0	_	0

available in market (Single and Double Slope) was only 1400 and 1800 ml/m^2/day for Dapoli, India. During night time, the temperature inside heating chamber of SBWSD was more due to insulation. Hence there was more condensation and consequently distillation was also more which contributes to the range of 60 to 150 ml in winter season and 200 to 300 ml in summer season.

Distillation efficiency

Efficiency of distillation unit in SBWSD was observed as 47.14% in November and 56.30% in April. More efficiency was observed in case of wick type than the bare collector as the water spread on the wick material is better than in the case of wick type. The plant gives maximum efficiency at 10° slope in summer season and at 40° slope in winter season.

Chemical analysis

Chemical analysis of impure (hostel tap and saline) and pure (distilled) water which were used for study was carried out for pH, EC, TDS (Mg^{2+}, Ca^{2+}, Na^+ ions etc.) depicted in Table 3. As can be observed from the table, chemical analysis of pure (distilled) and impure (saline or tap) water had a reduction in the pH, EC and various ions like Mg^{2+}, Ca^{2+}, Na^+, Cl^-, Carbonate, Bicarbonate etc. in the pure water.

Cost estimation

Energy calculations of SBWSD

The economic study of SBWSD was calculated on the basis of simple techno economic analysis shown in Table 4. This indicates that solar base distillation system is operated 250 days (except only in rainy days) in Konkan region in a year and produces 625 distilled water. Comparing electric operated distillation system, it consumes 450 electric units (1.8 × 250) to produce 625 L distilled water. In India, people have to pay Rs. 5 per electric unit (KWh) in the domestic sector. The total cost to operate electric base distillation unit to produce 625 L distilled water is Rs.2250.00. (Rs. 5 × 450). Hence, we could save Rs.2250.00 per year by utilizing this solar distillation system for obtaining distilled water and hence could save electricity in huge.

It was observed from Table 5 that the cost of the system is recovered within 7 months only, that is the payback period of the unit was only 0.6 years and after that the system will produce net profit. The observed economic indications as internal rate of returns (IRR) was 206%; Benefit cost ratio (BCR) for one year was 1.6, whereas net present worth (that is, the present value of future return) was Rs. 74607.9 for the end of 20th year

Table 4. Energy measures for techno economics of distillation systems.

Energy measure	Solar system	Electric system
Energy required to evaporate 2.5 L water $E = m \times C_p \times \Delta t + m \times \lambda$ m = Mass of water (2.5,kg) C_p = Specific heat of water (1 Kcal/kg/°C) Δt =Average temperature difference of water (52°C) λ = Latent heat of vaporization (540 Kcal/kg)	1.8 kWh	1.8 kWh
Energy required for 625 L distilled water in 250 days in a year (kWh)	450	450
Electricity tariff to produced 625 L distilled water in Rs.	-	2250/-
Revenue generated from 625 L distilled water at Rs.17	10625	10625
Net profit from system in Rs.	10625.00	8375.00

Table 5. Payback period analysis of SBWSD.

Year (1)	Cash outflow (2)	PW of cash outflow (at 12% discount rate) (3)	Cash inflow (4)	PW of cash inflow (at 12% discount rate) (5)	NPW [(5)-(3)]
0.0	5155.0	5155.0	0.0		-5155.0
1.0	500.0	446.4	10625.0	9486.6	9040.2
2.0	500.0	398.6	10625.0	8470.2	8071.6
3.0	500.0	355.9	10625.0	7562.7	7206.8
4.0	500.0	317.8	10625.0	6752.4	6434.6
5.0	1500.0	851.1	10625.0	6028.9	5177.8
6.0	500.0	253.3	10625.0	5383.0	5129.6
7.0	500.0	226.2	10625.0	4806.2	4580.0
8.0	500.0	201.9	10625.0	4291.3	4089.3
9.0	500.0	180.3	10625.0	3831.5	3651.2
10.0	1500.0	483.0	10625.0	3421.0	2938.0
11.0	500.0	143.7	10625.0	3054.4	2910.7
12.0	500.0	128.3	10625.0	2727.2	2598.8
13.0	500.0	114.6	10625.0	2435.0	2320.4
14.0	500.0	102.3	10625.0	2174.1	2071.8
15.0	1500.0	274.0	10625.0	1941.1	1667.1
16.0	500.0	81.6	10625.0	1733.2	1651.6
17.0	500.0	72.8	10625.0	1547.5	1474.6
18.0	500.0	65.0	10625.0	1381.7	1316.7
19.0	500.0	58.1	10625.0	1233.6	1175.6
20.0	0.0	0.0	10625.0	1101.5	1101.5
Total		4755.0		79362.8	74607.9

including 12% interest on system.

Conclusions

The average yield of distilled water from Single Basin Wick Type Solar Desalination Plant (SBWSD) was 2300 ml/m^2/day in winter season and 3400 ml/m^2/day in summer season at Dapoli, india. The efficiency of the SBWSD was observed to be 47.14% in winter season and 56.29% in summer season. The benefit cost ratio and payback period for SBWSD were observed to be 1.70 and 6 months, respectively.

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