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Performance of double slope solar still with external modifications

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ABSTRACT

External and internal modifications in the solar stills are undertaken by researchers to increase the efficiency. To keep the environmental factors constant and to study the impact of modification alone on efficiency, the experiment with modified solar stills were conducted simultaneously on the same day. The experiment was conducted at Villianur, Pondicherry, India, during the month of April 2016. For this purpose, four solar stills of identical dimensions were fabricated. Solar still I – a double slope solar still without external modification; solar still II – a double slope solar still connected with flat plate collector; solar still III – a double slope solar still fitted with external reflecting mirror and solar still IV – a double slope solar still connected with flat plate collector and fitted with reflecting mirror. The productive efficiency of solar still I was only 26.86%. Compared with solar still I, the increase in productivity of solar still IV was 104.43%. The performance of solar stills were traced and analysed from 8 a.m. to 5 p.m. The solar still II performed well even when solar intensity was low and solar still III performed well when solar intensity was high. Solar still IV performed well when solar intensity was both high and low. Nearly 66% of distillation occurred between 11 a.m. and 4 p.m. Only 17.2% of distillation occurred after 6 p.m.

Keywords: Desalination; Flat plate collector; Reflecting mirror; Solar still

1. Introduction

Distillation using solar energy in solar still is accepted as the low-cost and pollution-free technique to get pure water. But the efficiency of this technique is below the optimum level. Still there are wide scopes to improve the productivity. All over the world, many research works are going on to improve the productivity and to reach the optimum efficiency level. This experimental work is also a step towards this direction. Velmurugan and Srithar [1] integrated mini solar pond with solar still. The average daily production of distilled water increased considerably when the sponged solar still was integrated with mini solar pond. Voropoulus et al. [2] connected the solar pond with solar collector and solar still. It doubled the productivity. Somanchi et al. [3] used magnesium sulphate heptahydrate ($MgSO_4.7H_2O$) and sodium sulphate heptahydrate ($Na_2S.7H_2O$) as phase change materials and titanium oxide as energy storage material. Magnesium sulphate heptahydrate improved the efficiency of solar distillation. Nijmeh et al. [4] used various absorbing materials like violet dye, potassium permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$) in single slope solar still. The best result was obtained when violet dye was used. Swetha and Venugopal [5] added heat reservoir in the basin and used lauric acid as the phase change material in the single slope basin solar still. The increment in productivity was 13% when sand was used as heat reservoir and 36% when lauric acid was used as phase change material. Tamini [6] observed that the efficiency was about 20%–30% higher when the inner sides of the basin were covered with reflectors. El-Bahi and Inan [7] studied the performance of single slope basin type solar still with reflector on the

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whole inner surface and found it was 20% more productive. Al-Hayek and Badran [8] studied the effect of external reflector in basin type solar still and concluded that external reflector maintained higher reflectivity than the internal reflector. Tanaka and Nakatake [9] found that when internal and external reflectors were used, the amount of distillate averaged to 48% for the entire year. When internal reflector alone was used it was 22% only. Badran et al. [10] and Tiris [11] integrated a flat plate collector with the single basin solar still and the productivity of potable water was 52%. Joe Patrick Gnanaraj et al. [12] modified solar still by using fins, spreading coal and fitting reflecting mirror. The efficiency of solar still increased to 40% during low radiation days and 56% on high radiation days. Rai and Tiwari [13] proved that solar still integrated with flat plate collector increased output by 27%. Badran and Al-Tahaineh [14] proved that when flat plat collector was coupled with solar still, the efficiency increased by 35%. Dimri et al. [15] coupled a flat pipe with higher thermal conductivity material to produce higher output. Nafey et al. [16,17] used black rubber in solar still and black gravel for enhancing the productivity of solar still. The use of black rubber increased the productivity by 20% and black gravel by 19%. Sebaii et al. [18] used a baffle suspended absorber and the productivity increased by 20%. Velmurugan et al. [19] fabricated stepped solar still for desalinating the textile effluent. Fins, sponges, pebbles and a combination of above were used for enhancing the productivity of stepped solar still. Malaiyappan and Elumalai [20] increased the basin temperature by coupling helical copper coil, aluminum fins, hollow stainless steel tube and an iron plate with the basin. The solar still with aluminum fins had higher productivity compared with the one with the helical spherical coil and stainless steel tube. A combination of these modifications increased the productivity by 92%. Ayoub et al. [21] introduced a slowly rotating drum for the formation of thin water films that evaporate rapidly. During sunshine hours the yield increased 6–8 times. El-Maghlany et al. [22] studied the effect of radiation shape factor between the glass cover and saline water. The distillate productivity of the solar still with calculated radiation shape factor increased by about 9.0%–12.6% compared with the solar still that ignored radiation shape factor. Riahi et al. [23] evaluated the performance of double slope solar still integrated with 500 W heater to produce potable water. The integrated solar still produced about 6–10 times as much water as the conventional still. Riahi et al. [24] and Joe Patrick Gnanaraj and Ramachandran [25] observed that the performance of the conventional solar still can be improved by integrating fins to the basin liner of the still. The amount of distilled water produced increased by 11.8%.

The researchers design various internal and external modifications in the solar still to enhance the productivity. But it is very difficult to arrive at a meaningful comparison in the efficiency of solar still because the external environment that prevails in the experiment day influences the productivity. So, to make the comparison meaningful, the solar still with different modifications were tested on the same day. This keeps the environmental factors constant and the comparison becomes error free.

The objective of the study was to maximise the distillation by fabricating external modifications in the double slope solar still.

2. Experimental setup

For the experiment, four solar stills were fabricated. In one solar still, no external modification was done. In the other three solar stills, one or more external modifications were made. The efficiency of the four solar stills was tested simultaneously on the same day. In other words, the influence of the external environment on all the above four stills is the same.

To study the impact of external modifications in the performance of each of these solar stills, four solar stills of identical dimensions were fabricated. The outer dimension of each of these solar stills was 1 m × 0.6 m × 0.4 m and it was fabricated using low-cost wood. The thickness of the wooden box was 1.5 cm. Inside the wooden box the solar basin was placed. The solar basin was fabricated by using galvanised iron. The dimensions of the solar basin that were kept inside the wooden box were 0.9 m × 0.5 5 m × 0.38 m. To increase the absorption of solar radiation, the inner surface of solar basin was painted black. The gap between the outer wooden wall and the inner basin was filled by heat insulation materials like glass wool, thermocol and sponge. This was to retain the heat inside the basin and to restrict or minimise the diffusion of heat from the basin to external atmosphere.

The solar still has to permit maximum solar radiation into the solar basin throughout the day. For this purpose, a double slope glass cover was fabricated. The glass cover was made up of good quality transparent glass of thickness 4 mm. The slope of the solar still was maintained at 30°. To collect the distilled water, two collecting pipes were fitted in the solar still. To absorb and to retain the heat for longer period, pebbles were spreaded at the bottom of the solar still. This was to enhance the production and to sustain production for longer period.

3. External modifications

To increase the productivity of solar still, the following external modifications were attempted.

3.1. Reflecting mirror

External reflectors can be used to focus more solar radiation into the solar still. In this experiment, external reflecting mirror was used. A reflecting mirror of 0.20 m height, 0.6 m width and 6 mm thickness was fitted on a steel frame. It was fitted in the frame in such a manner that the angle of the mirror could be adjusted. The mirror was kept opposite to the incident of solar rays. The height and the angle of the mirror were so adjusted that maximum solar rays were reflected into the solar still.

3.2. Flat plate collector

The flat plate collector was a metal plate. The size of the plate was 1 m × 1 m × 45 m. A copper coil was fitted inside the flat plate and it was filled with pebbles, glass wool and red stone so as to absorb maximum temperature. The top surface of the plate was covered by a glass. The flat plate collector used in the experiment is shown in Fig. 1. The copper tube inside the flat plate collector was extended and inserted into

Fig. 1. Internal arrangement of flat plate collector.

the solar still. This arrangement enabled the transfer of heat energy from the flat plate collector to the solar still.

To compare the contribution of external modifications on the productivity of the solar still, the following four solar stills were designed.

Fig. 2. Double slope solar still without external modifications.

4. Design of various solar stills

4.1. Solar still I – a double slope solar still with no external modifications

In this experimental setup, the double slope solar still without external modification was used. The experimental setup is given in Fig. 2.

4.2. Solar still II – a double slope solar still connected with flat plate collector

In this experimental setup, a flat plate collector was connected with the double slope solar still. The experimental setup is given in Fig. 3.

4.3. Solar still III – a double slope solar still fitted with external reflecting mirror

In this experimental setup, additional solar rays were focused into the double slope solar still using a reflecting mirror. The experimental setup is given in Fig. 4.

4.4. Solar still IV – a double slope solar still fitted with external reflecting mirror and connected with flat plate collector

In this experimental setup, the double slope solar still was linked with flat plate collector and additional solar rays were focused using reflecting mirror. The experimental setup is given in Fig. 5.

Fig. 3. Double slope solar still with flat plate collector.

5. Experimental procedure

The four solar stills were placed for experiment during summer days. The experiment was conducted at Villianur, Pondicherry. In the morning, 5 L of saline water was poured into each solar still. In the evening at 5 p.m., the distilled water collected from each solar still was measured and recorded.

Fig. 4. Double slope solar still with external reflecting mirror.

Fig. 5. Double slope solar still with external reflecting mirror and flat plate collector.

In addition to this, the maximum temperature on the day of experiment was recorded. Further the glass temperature and water temperature in each solar still was measured at 2 p.m. and recorded for analysis. The same experiment was repeated for 7 d and all the above said readings were observed. The average performance during the 7 d was taken as the productivity of the solar still. The maximum temperature during the experimental days varied between 36°C and 39°C.

6. Theoretical calculation

6.1. Heat transfer for flat plate collector

The amount of solar radiation received by flat plate collector is [26]:

$$Q_i = I(t)A_c \tag{1}$$

where $I(t)$ is the intensity of solar radiation (W/m^2) and A_c is the flat plate collector area (m^2).

The rate of transmission of heat by the glass and the absorption rate of the absorber is [26]:

$$Q_i = I(t)\ (\alpha\tau)A_c \tag{2}$$

where α is the absorption coefficient of flat plate and τ is the transmission coefficient of flat plate.

The rate of internal heat loss by a flat plate collector is equal to the rate of heat transfer to solar still [26]:

$$Q_c = UA_c(T_c^4 - T_a^4) \tag{3}$$

where U = 20 W/m^2 K [10], convective heat transfer coefficient; A_c is the area of flat plate collector (m^2); T_c is the collector average temperature (K) and T_a is the ambient temperature (K).

6.2. Double slope solar still

The energy balance equations for the basin, water and glass are derived as follows.

6.2.1. Energy balance equation for basin

The energy received by basin plate in the solar still is the summation of energy gained by the basin plate and energy lost by convective heat transfer between basin and water and side losses Q_{loss}. This can be written as [1]:

$$A_b I(t) A_b \alpha_b = Q_{loss} + (mC_p\ [dT/dt])_b + Q_{c,b-w} \tag{4}$$

where A_b = 0.495 m^2, the area of the basin plate; α_b = 0.95, absorptivity of water [1]; m_b = 9 kg, mass of basin and:

$$I(t) = (I_g - I_d)\ (\cos\theta_i/\cos\theta_h) + I_d(1 + \cos\beta)/2 \tag{5}$$

where θ_i is the incidence angle of solar still and θ_h is the horizontal angle of solar still.

$$\theta_i = \cos^{-1}[\cos(\phi - \beta)\cos\delta\cos\omega\ \sin(\phi - \beta)\sin\delta] \tag{6}$$

$$\theta_h = \cos^{-1}[\cos\phi\cos\beta\cos\omega + \sin\phi\sin\delta] \tag{7}$$

where $C_{p,b}$ = 450 J/kg K, specific heat of basin.

The convective heat transfer between basin and water is written as [1]:

$$Q_{c,b-w} = h_{c,b-w}(T_b - T_w)A_b \tag{8}$$

$$h_{c,b-w} = (16.273 \times 10^{-3})\ (p_w - p_g)/(T_w - T_g)$$

Heat loss from basin to ambient is taken as [1]:

$$Q_{loss} = U_b(T_b - T_a)A_b \tag{9}$$

6.2.2. Energy balance equation for saline water

The energy received by saline water from sun and base is equal to the summation of energy gained by water, energy loss due to convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass and side losses [19].

$$A_w I(t)\alpha_w + Q_{c,b\text{–}w} = m_w C_{p,w} (\mathrm{d}T_w/\mathrm{d}t) + Q_{\text{loss}} + Q_{c,w\text{–}g} + Q_{r,w\text{–}g} + Q_{e,w\text{–}g} \quad (10)$$

where m_w = 5 kg, the mass of water in the solar still; α_w = 0.05, absorptivity of water from reference [1] and A_w is the area of water (m[2]).

Specific heat of saline water C_p can be taken from [1]:

$$C_{p,w} = a_1 + a_2 T_w + a_3 T_w + a_4 T_w \quad (11)$$

where a_1, a_2, a_3 and a_4 are taken as constant.

$$a_1 = 4208.8 - 6.6197s + 1.2288 \times 10^{-2} s^2 \quad (11a)$$

$$a_2 = -1.1262 + 5.4178 \times 10^{-2} s - 2.2719 \times 10^{-4} s^2 \quad (11b)$$

$$a_3 = 1.2026 \times 10^{-2} - 5.5366 \times 10^{-4} s - 1.8906 \times 10^{-6} s^2 \quad (11c)$$

$$a_4 = 6.877410^{-7} + 1.517 \times 10^{-6} s - 4.4268 \times 10^{-9} s^2 \quad (11d)$$

Heat transfer for side loss is as follows [1]:

$$Q_{\text{loss}} = U_b (T_b - T_w) A_w \quad (12)$$

where U_b = 14 W/m[2] K, convective mass transfer coefficient [1].

Convective heat transfer between water and glass can be calculated by the following formula [19]:

$$Q_{c,w\text{–}g} = h_{c,w\text{–}g} (T_w - T_g) A_w \quad (13)$$

$$h_{(c,W-g)} = 0.884 \left[T_W - T_g + \frac{(P_W - P_g)(T_W + 273)}{3 \times 10^3 - P_W} \right]^{1/3}$$

where T_w is the water temperature (°C) and T_g is the glass temperature (°C).

$$P_w = 7235 - 431.45 T_w + 10.76 T_w^{\,2} \quad (14)$$

where P_w is the saturated pressure at condensing glass surface (N/m[2]) [23].

$$P_g = 7235 - 431.45 T_g + 10.76 T_g^{\,2} \quad (15)$$

where P_g is the saturated pressure at condensing glass cover (N/m[2]) [23].

Radiative heat transfer between water and glass can be calculated by the following formula [19]:

$$Q_{r,w\text{–}g} = \sigma\varepsilon (T_w^{\,4} - T_g^{\,4}) A_w \quad (16)$$

where σ = 5.67 × 10^{-8} W/m[2] K[4], Stefan–Boltzmann constant; $\varepsilon_{\text{eff}} = (1/\varepsilon_w + 1/\varepsilon_g)^{-1}$; T_w is the water temperature (K) and T_g is the glass temperature (K).

Heat transfer for evaporation water and glass can be calculated by the following formula [1]:

$$Q_{e,w\text{–}g} = h_{e,w\text{–}g} (T_w - T_g) A \quad (17)$$

$$h_{e,w\text{–}g} = (16.273 \times 10^{-3})\, h_{c,w\text{–}g}\, (p_w - p_g)/(T_w - T_g)$$

6.2.3. Energy balance equation of glass of the solar still

Energy gained by glass cover is equal to the summation of the energy losses by radiative heat transfer between glass and sky, the energy losses by convective heat transfer between glass and sky and the energy gained by glass [1].

$$A_g I(t)\alpha_g + Q_{r,w\text{–}g} + Q_{c,w\text{–}g} + Q_{e,w\text{–}g} = Q_{r,g\text{-sky}} + Q_{c,g\text{-sky}} + m_g C_{p,g} (\mathrm{d}T/\mathrm{d}t)_g \quad (18)$$

where α_g = 0.06, the absorptivity of the glass given by reference [1]; A_g = 1.45 m[2], area of glass cover and $C_{p,g}$ = 850 J/kg K, specific heat of basin.

Heat transfer by radiation between glass and sky [1]

$$Q_{r,g\text{-sky}} = \sigma\varepsilon_{\text{eff}} (T_g^{\,4} - T_{\text{sky}}^{\,4}) A_g \quad (19)$$

where σ = 5.67 × 10^{-8} W/m[2] K[4], Stefan–Boltzmann constant; T_{sky} is the glass temperature of sky (°C) and T_g is the water temperature (°C).

$$\varepsilon_{\text{eff}} = (1/\varepsilon_{\text{ug}} + 1/\varepsilon_{\text{lg}})^{-1} \quad (20)$$

In the above said equation ε_{lg} is the lower glass emissivity; ε_{ug} is the upper glass emissivity; T_{sky} is the temperature of sky (°C) and T_a is the ambient temperature (°C).

$$T_{\text{sky}} = T_a - 6 \quad (21)$$

Initially the water temperature, basin temperature and glass temperature are taken as ambient temperature. The change in water temperature (dT_w), basin temperature (dT_b) and glass temperature (dT_g) are noted. These values are substituted in Eqs. (4), (10) and (18). By using the MATLAB programme Eqs. (4), (10) and (18) were solved.

The internal heat loss in flat plate collector is equal to the sensible energy received by solar still.

6.3. The total condensation

The total condensation rate was calculated by formula given below [1]:

$$\frac{dm_c}{dt} = \frac{h_{e,w-g}\left(T_w - T_g\right)}{h_{fg}} \quad (22)$$

where h_{fg} can be calculated from the following equations [1]:

$$h_{fg} = (597.49 - 5.6625 \times 10^{-1} T_w + 1.5082 \times 10^{-4} T_w^{\,2} - 3.2764 \times 10^{-6} T_w^{\,3}) \times 4.1868 \quad (23)$$

For next time, the parameters are redefined as:

$$T_w = T_w + dT_w \quad (24)$$

$$T_g = T_g + dT_g \quad (25)$$

$$T_b = T_b + dT_b \quad (26)$$

6.4. Total sensible energy gained by the solar still

Total sensible energy gained = energy rise during direct heating in still + sensible energy coming from flat plate collector + energy from reflecting mirror.

7. Results and discussion

7.1. Solar still I

In this experiment, only the double slope solar still was taken. No external modification was added to it. The result of the experiment was recorded in Table 1.

At 2 p.m. the water in the solar still reached a maximum temperature of 76°C. Water temperature ranged between 72°C and 76°C. The average maximum water temperature reached was 74°C. In the meantime, the glass temperature was also measured. The glass temperature ranged between 68°C and 72°C. The average maximum glass temperature was 69.71°C. The output of distilled water was measured in the evening. The output of water ranged between 1.2 and 1.5 L depending upon the maximum temperature of the day. The average daily output was 1.34 L. The daily efficiency reached a maximum of 30% and it varied between 24% and 30%. The average daily efficiency was 26.86%.

7.2. Solar still II

In this experiment, the double slope solar still was connected with the flat plate collector. A copper tube from the flat plate collector was inserted into the solar still. It was coiled around the internal wall of the solar basin and coil was kept 2 cm above the water level. This arrangement enabled the transfer of heat energy from the flat plate collector to the water in the solar basin. The performance of the solar still was recorded in Table 2.

Water in the solar basin reached a maximum temperature of 77°C. The average maximum water temperature was 75.14°C that was 1.14°C higher than the solar still I. The output of water reached a maximum of 2.5 L. It varied between 2.2 and 2.5 L. The average output per day was 2.33 L. The daily efficiency reached a maximum of 50%. And it ranged between 44% and 50%. The average efficiency was 46.57%.

Table 1
Double slope solar still with no external modification

S. No.	Date	Maximum temperature (°C)	Water temperature (°C)	Glass temperature (°C)	Input water (L)	Output after 9 h (L)	Daily efficiency (%)
1	2 April 2016	36	72	68	5	1.2	24
2	3 April 2016	37	73	69	5	1.3	26
3	4 April 2016	38	73	69	5	1.3	26
4	5 April 2016	38	73	69	5	1.4	28
5	8 April 2016	39	76	71	5	1.5	30
6	9 April 2016	38	75	70	5	1.3	26
7	10 April 2016	38	76	72	5	1.4	28
Average			74.00	69.71	5.00	1.34	26.86

Table 2
Double slope solar still with flat plate collector

S. No.	Date	Maximum temperature (°C)	Water temperature (°C)	Glass temperature (°C)	Input water (L)	Output after 9 h (L)	Daily efficiency (%)	Increase in efficiency (%)
1	2 April 2016	36	73	70	5	2.2	44	64
2	3 April 2016	37	75	71	5	2.2	44	64
3	4 April 2016	38	75	71	5	2.3	46	72
4	5 April 2016	38	74	71	5	2.4	48	79
5	8 April 2016	39	77	73	5	2.5	50	87
6	9 April 2016	38	76	72	5	2.4	48	79
7	10 April 2016	38	76	73	5	2.3	46	72
Average			75.14	71.57	5.00	2.33	46.57	73.77

The average daily efficiency of solar still II was higher than the solar still I by 73.77%.

7.3. Solar still III

In this experiment, the double slope solar still was fitted with an external mirror. This enabled the focusing of additional solar rays into the solar still. The performance of the solar still with this modification was recorded in Table 3.

The water in the solar still reached a maximum of 79°C. It varied between 75°C and 79°C depending upon the maximum temperature of the day. The average maximum temperature was 77.43°C. When external mirror was fitted with solar still, the water temperature increased from 74°C to 77.43°C. There was also improvement in the performance of the solar still. The water output reached a maximum of 2.6 L. The average output was 2.43 L. In other words, the daily efficiency reached a maximum of 52%. The average daily efficiency was 48.57%. The efficiency of the solar still III was higher than the solar still I by 81.45%.

7.4. Solar still IV

In this experiment, the double slope solar still was linked with flat plat collector. Further additional solar rays were focused into the solar still using external mirror. The performance of solar still with these modifications was recorded in Table 4.

The water temperature in the solar still reached a maximum of 83°C. On all the 7 d when the experiment was conducted, the maximum water temperature was above 80°C and it ranged between 80°C and 83°C. The average maximum water temperature was 81.29°C. There was spectacular improvement in the performance of the solar still. The output reached a maximum of 2.9 L. It ranged between 2.6 and 2.9 L. The average daily output was 2.74 L. The efficiency of the solar still reached a maximum of 58%. The average daily efficiency was 54.86%. The efficiency of solar still IV was higher than the solar still I by 104.43%. When solar still alone was used, the daily efficiency was 26.86%. When flat plate collector was linked with solar still, the performance improved to 46.57%. When the external mirror was fitted with solar still, the performance reached 48.57%. When the double slope solar still was linked with flat plate collector and additional solar rays were focused, the performance reached a maximum of 54.86%.

7.5. Daily efficiency (%)

Daily efficiency is the ratio between output of water collected from the solar still to the input of saline water.

Table 3
Double slope solar still with external reflecting mirror

S. No.	Date	Maximum temperature (°C)	Water temperature (°C)	Glass temperature (°C)	Input water (L)	Output after 9 h (L)	Daily efficiency (%)	Increase in efficiency (%)
1	2 April 2016	36	75	70	5	2.3	46	72
2	3 April 2016	37	77	72	5	2.3	46	72
3	4 April 2016	38	77	73	5	2.4	48	79
4	5 April 2016	38	78	73	5	2.5	50	87
5	8 April 2016	39	79	74	5	2.6	52	94
6	9 April 2016	38	78	74	5	2.5	50	87
7	10 April 2016	38	78	73	5	2.4	48	79
Average			77.43	72.71	5.00	2.43	48.57	81.43

Table 4
Double slope solar still with external reflecting mirror and flat plate collector

S. No.	Date	Maximum temperature (°C)	Water temperature (°C)	Glass temperature (°C)	Input water (L)	Output after 9 h (L)	Daily efficiency (%)	Increase in productivity (%)
1	2 April 2016	36	80	74	5	2.6	52	94
2	3 April 2016	37	81	77	5	2.7	54	101
3	4 April 2016	38	82	77	5	2.7	54	101
4	5 April 2016	38	82	78	5	2.8	56	109
5	8 April 2016	39	83	78	5	2.9	58	116
6	9 April 2016	38	80	76	5	2.7	54	101
7	10 April 2016	38	81	77	5	2.8	56	109
Average			81.29	76.71	5.00	2.74	54.86	104.43

Daily efficiency = (output of water/input of water) × 100

Theoretically daily efficiency can be calculated by using the formula:

Daily efficiency = $\Sigma(m_e h_{fg})/\Sigma A_s I(t)$

7.6. Increase in productivity (%)

Increase in productivity = ([output of the modified solar still – output of the solar still without modification]/[output of the solar still without modification]) × 100.

Performance of the solar still with modification is compared with the performance of the solar still without modification. The increase in the output of the modified solar still over the solar still without modification is regarded as the increase in efficiency.

7.7. Graphical representation of the performance of solar stills

The following graphs show the performance of the solar stills.

7.7.1. Atmospheric temperature and efficiency

The efficiency of the solar stills varies with atmospheric temperature. When atmospheric temperature increases, other things remaining constant, the performance of the solar still increases. The relationship between atmospheric temperature and efficiency is given in Fig. 6.

As the atmospheric temperature increases the efficiency of the solar still also increases. There is positive relationship between atmospheric temperature and efficiency. Further, it is clear that the external modification integrated with the solar still also increases the efficiency. The efficiency of the solar still without any modification was low. When it was linked with flat plate collector there was improvement in the productivity. When external mirror was fitted with the solar still there was further improvement in the efficiency. The integration of the solar still with flat plate collector and external mirror brought very high increase in efficiency of the solar still. This shows that external modifications are necessary to increase the efficiency and enhance the performance towards the optimum level.

7.7.2. Atmospheric temperature and increase in productivity

When external modifications were made the performance improved. The efficiency of the modified solar stills was high compared with the performance of the solar still without modification. Increase in the productivity of the modified solar stills is given in Fig. 7.

The increase in productivity of solar still III was higher than the productivity of solar still II. The increase in productivity of the solar still IV was higher than the increase in productivity of solar stills II and III.

7.7.3. External modification and efficiency

The external modification made in the solar stills increased the efficiency of solar still. The average performances of the solar stills are shown in Table 5 and Fig. 8.

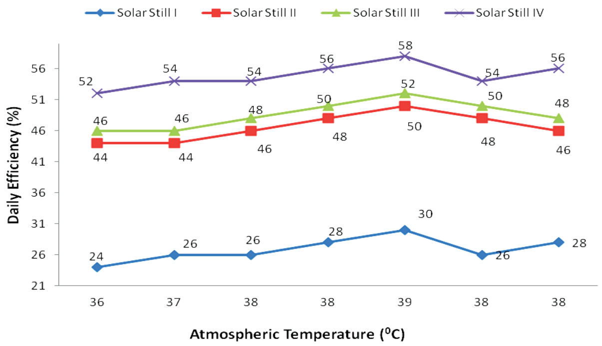

Fig. 6. Comparison of atmospheric temperature and daily efficiency.

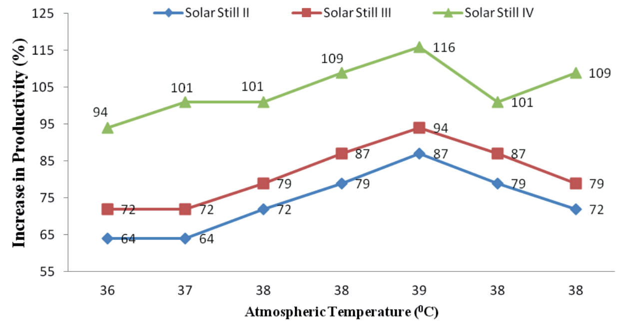

Fig. 7. Increase in productivity of the modified solar stills in different atmospheric temperatures.

Table 5
Average performances of the solar stills

S. No.	Modification	Efficiency (%)
1	No external modification	26.86
2	Linked with flat plate collector	46.57
3	Fitted with reflecting mirror	48.57
4	Linked with flat plate collector and mirror	54.86

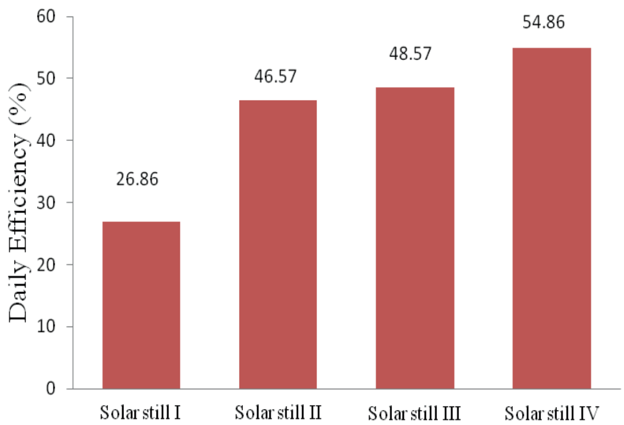

Fig. 8. External modification and efficiency.

The average performance of the solar still I was only 27%. The external modifications integrated with solar stills increased the efficiency. It reached a maximum of 55% in solar still IV.

8. Calculation of theoretical efficiency

The theoretical efficiency level was calculated by taking into consideration the initial mass and final mass of the solar basin and bottom surface area of the solar basin.

8.1. Solar still I

At 8 a.m. the mass of the double slope solar still without any external modification was 16 kg and the mass of the same still at 5 p.m. was 13 kg. Bottom surface area was 0.495 m^2. The theoretical efficiency of the solar still I was 30%.

8.2. Solar still II

The mass of the double slope solar still with flat plate collector at 8 a.m. was 16 kg and the mass at 5 p.m. was 12 kg. Still had a bottom surface area of 0.495 m^2. So the theoretical efficiency from this setup was 52%.

8.3. Solar still III

When the experiment was started at 8 a.m. the mass of the double slope solar still with external mirror was 16 kg. At 5 p.m. the mass was 10.3 kg. Bottom surface area of the still was 0.495 m^2. So the theoretical efficiency was 62%.

8.4. Solar still IV

At 8 a.m. the mass of the double slope solar still with external mirror and flat plate collector was 16 kg and the mass at 5 p.m. was 9 kg. Bottom surface area was 0.495 m^2. The theoretical efficiency from solar still IV was 71%.

9. Comparison of experimental efficiency with theoretical efficiency

It is always better to compare the theoretical value with experimental value. Theory prescribes the maximum that can be achieved. But in practice the performance is generally lower. Table 6 shows the comparison of the experimental and theoretical efficiency values.

The experimental value achieved is always lower than the theoretical value. There is gap between the two. This may be due to some leakages in the experimental setup. If these leakages are plugged, we can move towards optimum efficiency level. This shows that there are still ample opportunities to increase the productivity. Further research work will concentrate in this area.

10. Comparative analysis of initial water and distilled water

pH value of initial water was 10.99. It declined to 4.99 in the distilled water. The total dissolved salt present in the initial water was 840 mg/L. It declined to 13 mg/L in the distilled water. Before distillation the total hardness was 71 mg/L. The distilled water was free from hardness.

11. Comparative performance of the solar stills

The performances of the four solar stills were recorded at 11 a.m., 1 p.m., 3 p.m. and 5 p.m. Table 7 depicts the performance of the solar stills.

The experiment was started at 8 a.m. Performance of the solar stills up to 11 a.m. was very low. As the solar intensity increased, the performance also increased. Between 1 p.m. and 3 p.m. the performance was maximum. After 3 p.m. the performance declined because the solar intensity declined.

The performance of the solar still II was higher than the performance of solar still I and solar still III after 3 p.m. because the latent heat produced by flat plate collector sustained the performance. But the performance of the solar still III was higher than the performance of solar still I and solar still II between 11 a.m. and 3 p.m. because the external reflecting mirror enhanced the intensity of heat. Solar still I (without modification) produced only 0.29 L of distilled water between 3 p.m. and 5 p.m. When the solar still was linked with flat plate collector, distilled water produced increased to 0.55 L. On the other hand, solar still I produced only 0.85 L between 11 a.m. and 3 p.m. But solar still III (fitted with mirror) produced 1.65 L of distilled water. This shows that when solar intensity is high external mirror increases the yield and flat plate collector sustains the yield when solar intensity is low. In solar still IV, the external reflecting mirror enhanced the yield when the solar intensity was high and the flat plate collector sustained the yield when the solar intensity was low. As a result the output was high compared with other solar stills. Fig. 9 explains the performance of the four solar stills.

Table 6
Comparison of experimental and theoretical efficiencies

S. No.	Modifications	Daily efficiency (%)		Gap (%)
		Experimental value	Theoretical value	
1	Double slope solar still without modifications	27	30	3
2	Double slope solar still with flat plate collector	47	52	5
3	Double slope solar still with reflecting mirror	49	62	13
4	Double slope solar still with flat plate collector and reflecting mirror	55	71	16

Table 7
Comparative performance of the solar stills

S. No.	Time interval (h)	Solar still I		Solar still II		Solar still III		Solar still IV	
		Output (L)	Performance (%)	Output (L)	Performance (%)	Output (L)	Performance (%)	Output (L)	Performance (%)
1	Up to 11 a.m.	0.20	14.9	0.31	13.1	0.30	12.3	0.33	11.9
2	11 a.m.–1 p.m.	0.38	28.1	0.63	26.9	0.72	29.8	0.74	27.0
3	1 p.m.–3 p.m.	0.47	35.3	0.84	36.2	0.93	38.2	1.02	37.1
4	3 p.m.–5 p.m.	0.29	21.7	0.55	23.8	0.48	19.7	0.65	24.0
Total		1.34	100.0	2.33	100.0	2.43	100.0	2.74	100.0

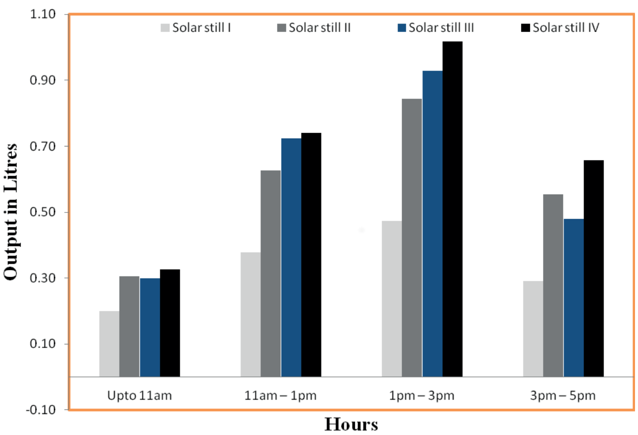

Fig. 9. Relative performance of solar stills.

The performance of the solar stills increased up to 3 p.m. but after 3 p.m. the performance declined.

12. Performance of solar still IV in a day recorded for every 1 h

Solar still IV was the best performing solar still. So its performance was recorded for 24 h. To assess the performance of the solar still the experiment was conducted on 15 June 2016, at Pondicherry, India. The experiment was started at the eighth hour. Initially, 5 L of saline water was poured into the solar still. The following particulars were recorded in Table 8 for every hour. Solar radiation in the still $I(t)$ (W/m^2), solar radiation in the flat plate collector $I_c(t)$ (W/m^2), water temperature in the still T_w (°C), inside surface temperature of the solar still T_i (°C), outside surface temperature of the solar still T_o (°C), vapour temperature of the solar still T_v (°C), inside surface temperature of the flat plate collector T_{ci} (°C), outside surface temperature of the flat plate collector T_{co} (°C) and relative humidity (RH).

There was no production of distilled water between 8 a.m. and 9 a.m. After 9 a.m. the solar still started producing distilled water. The performance slowly improved and reached the maximum between 1 p.m. and 2 p.m. Then it started declining. 66% of the distillation occurred between 11 a.m. and 4 p.m. 17.2% distillation occurred after 6 p.m.

13. Comparison with previous research works

A comparison of the research work is done with the earlier research work.

13.1. Increase in productivity

The increase in productivity achieved by the different research works when external or internal modifications were integrated with solar still was compared with the experimental result. The comparison is shown in Table 9.

In the previous research work the betterment of productivity was 50% or less. But this research work witnessed 104% improvement in productivity.

14. Error analysis

With the help of calibrated constant copper thermocouples, the temperature of vapour, water, glass and collector inlet and outlet were measured. The outer glass and ambient temperatures were measured by a calibrated mercury thermometer. The output water was measured with the help of measuring jar. The solar intensity was recorded with the help of a calibrated solarimeter. The hygrometer was used for measuring the relative humidity within the solar basin. The least counts and ranges of measuring instruments are shown in Table 10.

15. Conclusion

In the double slope solar stills external modifications were made. The productivity of the solar still without any external modification was only 26.86%. The productivity increased to 46.57% when it was connected with flat plate collector. The fitting of external mirror enhanced the productivity to 48.57%. When the double slope solar still was linked with flat plate collector and fitted with external mirror the productivity reached 54.86%.

The increase in the productivity of the modified solar stills was compared with the productivity of unmodified solar still. The productivity of solar still linked with flat plate collector was 73.77% higher than solar still I. It was 81.43% higher when external mirror was fitted. The productivity increased to 104.43% when the modifications of both flat plate collector and external mirror were added in the still.

The trend in the production of the four stills were traced from 8 a.m. to 5 p.m. and analysed. The production increased

Table 8
Performance of solar still IV in 24 h

S. No.	Time	$I(t)$ (W/m²)	$I_c(t)$ (W/m²)	T_w (°C)	T_i (°C)	T_o (°C)	T_v (°C)	T_{ci} (°C)	T_{co} (°C)	Output (L)	RH
1	8 a.m.–9 a.m.	570	695	42.84	48.35	40.14	45.67	41.94	59.92	0	0.76
2	9 a.m.–10 a.m.	765	880	59.69	61.3	48.89	61.45	58.79	76.06	0.06	0.79
3	10 a.m.–11 a.m.	930	1,025	70.1	67.5	53.86	67.56	69.2	86.18	0.16	0.86
4	11 a.m.–12 a.m.	1,010	1,100	80.11	69.01	53.53	73.78	73.42	89.68	0.3	0.9
5	12 a.m.–1 p.m.	995	1,060	79.91	69.57	50.95	70.53	73.01	86.94	0.42	0.9
6	1 p.m.–2 p.m.	905	970	74.36	67.27	49.78	68.94	70.46	82.15	0.72	0.9
7	2 p.m.–3 p.m.	750	845	72.34	63.5	48.35	65.32	66.4	76.22	0.6	0.9
8	3 p.m.–4 p.m.	530	640	63.14	59.8	46.65	60.54	62.24	66.28	0.32	0.9
9	4 p.m.–5 p.m.	305	–	59.25	56.32	43.12	57.28	–	–	0.21	1
10	5 p.m.–6 p.m.	155	–	54.25	51.88	41.15	54.43	–	–	0.19	1
11	6 p.m.–7 p.m.	60	–	49.48	47.92	39.52	48.78	–	–	0.15	1
12	7 p.m.–8 p.m.	–	–	45.66	44.65	38.45	45.34	–	–	0.12	0.9
13	8 p.m.–9 p.m.	–	–	42.27	41.61	37.15	41.78	–	–	0.09	1
14	9 p.m.–10 p.m.	–	–	39.56	39.49	35.21	39.45	–	–	0.06	1
15	10 p.m.–11 p.m.	–	–	37.65	38.22	34.08	37.41	–	–	0.05	1
16	11 p.m.–12 p.m.	–	–	36.25	37.11	33.56	36.31	–	–	0.03	1
17	12 p.m.–1 a.m.	–	–	35.25	36.41	32.85	35.62	–	–	0.03	0.9
18	1 a.m.–2 a.m.	–	–	34.65	36.11	32.43	34.89	–	–	0.02	1
19	2 a.m.–3 a.m.	–	–	34.23	35.91	32.25	34.5	–	–	0.02	0.9
20	3 a.m.–4 a.m.	–	–	33.95	35.78	32.11	34.12	–	–	0.01	0.9
21	4 a.m.–5 a.m.	–	–	33.85	35.73	31.89	33.87	–	–	0.001	0.9
22	5 a.m.–6 a.m.	30	–	33.73	35.66	31.51	33.56	–	–	0.001	0.9
23	6 a.m.–7 a.m.	90	–	33.85	36.83	32.92	34.67	–	–	0.013	0.9
24	7 a.m.–8 a.m.	294	–	34.6	39.65	34.48	36.57	–	–	0.025	0.88
		$\Sigma I(t)$ = 7,389	$\Sigma I_c(t)$ = 7,135							ΣP = 3.60	

Table 9
Comparison of increase in productivity

S. No.	Solar still modifications	Author	Increase in productivity (%)
1	Internal and external reflecting mirror	Tanaka and Nakatake [9]	48
2	Internal reflecting mirror	Tamini [6]	20–30
3	Internal reflecting mirror	Al-Hayek and Badran [8]	20
4	External solar pond and solar collector	Voropoulus et al. [2]	29
5	In this work		104 (Avg.)

Table 10
Ranges and accuracy

S. No.	Instrument	Accuracy	Range	Error (%)
1	Thermocouple	0.1°C	0°C–100°C	0.20
2	KippZonen solarimeter	±1 W/m²	0–4,000 W/m²	0.20
3	Collection tank	±0.2 L	0–25 L	10
4	Measuring jar	1 mL	0–1,000 mL	5
5	Hygrometer	1	0–100	1
6	Thermometer	±1°C	0°C–100°C	0.2

up to 3 p.m. and then it decreased. The still linked with flat plate collector sustained production even after 3 p.m. when the solar intensity started diminishing. The solar still fitted with external mirror accelerated production between 11 a.m. and 3 p.m. when the solar intensity was high. The solar still fitted with both the modifications sustained production throughout the day.

The performance of the solar still IV (with flat plat collector and external mirror) was recorded for 24 h. The performance started increasing from 9 a.m. to 2 p.m. Then it started declining. 66% of the output that is two-third of the output was produced between 11 a.m. and 4 p.m. 17.2% of the distillation was done after 6 p.m.

To conclude, the double slope solar still externally modified by linking it with flat pipe collector and external mirror substantially enhanced the distillation. Further these two modifications sustained distillation for a longer duration.

Symbols

A	—	Area, m^2
A_b	—	Area of basin, m^2
A_g	—	Area of glass, m^2
A_w	—	Area of water, m^2
A_c	—	Area of flat plate collector, m^2
C_p	—	Specific heat, J/kg K
P	—	Partial pressure, N/m^2
Q	—	Heat transfer, W
Q_i	—	Collector heat input, W
Q_c	—	Heat loss by flat plate collector, W
T	—	Temperature, °C
dt	—	Time interval, s
I_g	—	Global radiation intensity plate, W/m^2
P_g	—	Saturated vapour pressure at glass surface, N/m^2
P_w	—	Saturated vapour pressure at water surface, N/m^2
$I(t)$	—	Hourly average of incident radiation on still, W/m^2
$I_c(t)$	—	Hourly average of incident radiation on collector, W/m^2
h	—	Heat transfer coefficient, W/m^2 K
h_{fg}	—	Enthalpy of evaporation, J/kg
m_c	—	Condensate, kg/m^2
m	—	Mass, kg
U	—	Side heat loss coefficient, W/m^2 K
T_w	—	Water temperature, °C
T_{ci}	—	Inner temperature of condensing covers, °C
T_{co}	—	Outer temperature of condensing covers, °C
T_a	—	Ambient temperature, °C
T_v	—	Temperature of vapour in the solar still, °C
T_{ci}	—	Temperature of flat plate collector inlet, °C
T_{co}	—	Temperature of flat plate collector outlet, °C

Greek

σ	—	Stefan–Boltzmann constant, $W/m^2 K^4$
ε	—	Emissivity
α	—	Absorptivity
τ	—	Transmission

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