Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20583

80 (2017) 27–40
June

Optimization on performance of single-slope solar still linked solar pond via Taguchi method

S. Joe Patrick Gnanaraj, S. Ramachandran*

*Department of Mechanical Engineering, Sathyabama University, Chennai, Tamilnadu, India,
emails: aishram2006@gmail.com (S. Ramachandran), gnanaraj.134@gmail.com (S.J.P. Gnanaraj)*

Received 5 September 2016; Accepted 6 February 2017

ABSTRACT

The efficiency of the solar still is below optimum. To increase the efficiency and to reach the optimum performance many modifications and improvements in the solar stills were attempted. In this research work, a mini solar pond was linked with the solar still. Further with the help of mirrors, solar radiations were reflected into the solar pond and solar still. Four parameters that were influencing the performance of the solar still and their levels were identified. They were: parameter I – sodium chloride concentration level (1.5, 2.5 and 3.5 kg), parameter II – mini solar pond zone (lower converting zone (LCZ), middle converting zone and upper converting zone), parameter III – angle of the reflecting mirror at the bottom of the still (–15°, 0° and 15°) and parameter IV – angle of the mirror fitted in the pond (90°, 113° and 135°). Taguchi method was used to select the best performing levels. S/N ratios and mean performance of the different levels indicated that level 3 of parameter I, level 1 of parameter II, level 2 of parameter III and level 3 of parameter IV were the best performing levels. The regression analysis also confirmed that the above levels of the four parameters had positive regression coefficient. So optimum distillate yield can be obtained when the sodium chloride concentration level was 3.5 kg, the solar still was linked with LCZ of the pond, the reflecting angle at the bottom of the still was kept at 0° and the mirror at the pond at 135°. Combining the above selected levels of the four parameters, the experiment was conducted, and the distillate output obtained was 3.26 L/d. It was 95.54% higher than the yield of the conventional still. The theoretical values were compared with the experimental results, and there was good agreement between the two.

Keywords: Desalination; Reflecting mirror; Solar pond; Solar still; Taguchi method

1. Introduction

The scarcity for potable drinking water has increased worldwide due to the huge increase in industries and population. Desalination is a process to convert saline water into drinking water. One of the methods of performing desalination is by using solar stills.

The performance of solar still mainly depends on the intensity of solar radiation. Internal modifications are made in the solar still to absorb more heat energy from solar radiation. To enhance the performance of solar still, heat energy can be supplied from some external source also. The unutilized heat energy emitted by the industries in the atmosphere can be channelized for this purpose. But their availability is limited and location specific. On the other hand, solar pond can be fabricated at any place and the heat energy stored in the pond can be used to enhance the distillation in the solar still. Further with the help of mirrors, solar rays can be focused into the pond and still to improve their performance.

The distillate yield of a solar still is influenced by ambient temperature, insulation, velocity of the wind, dust and cloud ambient condition, basin water depth, concentration of salt in the water, inlet temperature of water, water and glass temperature difference, water free surface area, absorber flat

* Corresponding author.

area and glass angle. The solar intensity, velocity of wind, ambient temperature dust and cloud ambient condition are metrological parameters, and they cannot be controlled. The other factors can be varied to optimize the performance of the still.

The parameters we choose to optimize the performance of the still will perform differently at different levels. The success of solar distillation depends on the selection of the best performing level in each parameter. Taguchi method helps to identify the best performing levels of the parameters we choose to optimize the performance of the still.

The objective of this study was to optimize the performance of the solar pond linked solar still assisted by mirrors at the top of the pond and at the bottom of the still. With the help of Taguchi method the best performing levels of the parameters that influence the performance of the still were identified. By combining the best performing levels, the experiment was conducted, and the experimental results were compared with the theoretical values.

The factorial experimentation is very useful in research work. It is based on strong and sound statistical foundation. But this technique becomes unmanageable in the industrial contexts. With increase in the number of factors and the levels, the number of experiment would be large. To solve this issue, statisticians have developed factorial replicate designs (fractional factorial designs). But this requires good statistical knowledge on the part of experimenter, and it is subject to some constrains that limit the applicability.

Dr. Genichi Taguchi, a Japanese scientist contributed significantly to the field of quality engineering. According to him the product design should be such that the performance is insensitive to uncontrollable (noise) factors. The orthogonal arrays (OAs) are suggested by Taguchi for designing the experiments. The main advantage of these designs lies in their simplicity and easy adaptability to complex experiments involving number of factors with numbers of levels. The desired information can be obtained with minimum number of trails.

El-Sebaii et al. [1] integrated a single-slope single-basin solar still with a shallow solar pond, and the productivity was increased by 52.36%. Appadurai and Velmurugan [2] integrated a fin type solar pond with a fin type solar still, and the distillate output was increased by 50%. Malaiyappan and Elumalai [3] used a semipermeable membrane, and a solar pond to enhance the productivity of a single-slope single-basin solar still. Velmurugan and Srithar [4] concluded that the average distillate productivity of a mini solar pond integrated solar still with sponge was 57.8% more than the productivity of ordinary still. It was found that the optimum value of salt concentration in mini solar pond is 80 g/kg. Velmurugan et al. [5] evaporated industrial effluent with the help of a fin type single-basin solar still and a stepped solar still and integrated mini solar pond with these stills. When mini solar pond, pebbles, sponges and fins were used in stepped solar still, maximum productivity was achieved. Velmurugan and Srithar [6] concluded that mini solar pond increased the productivity of a solar still by around 59%. Tamini [7] modified the solar still with internal and external reflecting mirrors, and the efficiency was increased by 20%–30%. Al-Hayek and Badran [8] compared single-slope solar still, fitted with reflecting mirror and double slope solar still without any modifications. The single-slope still with modification was 20% more efficient. El-Swify and Metias [9] fabricated two solar stills of the same dimensions – one was conventional type which produced an efficiency of 22%, the second one was modified by adding reflecting mirror which resulted in an efficiency of 83%. Prakash and Velmurugan [10] modified the solar still by fitting two reflecting mirrors. The efficiency was 29.2% with reflectors alone, the efficiency was 38.68% with combination of reflectors and gravel, and the efficiency was 41.6% with combination of reflectors and pebbles. Tanaka [11] used internal and external reflectors in basin type solar still, and productivity was increased by 70%–100% on winter days. Omara et al. [12] used internal and external mirror in a stepped still, and the performance of the modified stepped solar still was compared with the conventional still. The performance of the modified stepped still increased approximately by 125%. Abdallah et al. [13] modified the conventional solar still by installing reflecting mirrors on all internal sides. The flat basin was replaced by a stepwise basin, and the performance was enhanced up to 180%. Omara et al. [14] fixed mirrors in the vertical side of the steps of a stepped solar still, and the productivity of the modified stepped solar still was higher than the conventional still approximately by 75%. Tanaka [15] found that the productivity of the solar still could be enhanced throughout the year by changing the angle of the external reflectors. Gupta and Singh [16] used Taguchi and ANOVA method to investigate the effect of process parameters on productivity. Water temperature and salt concentration were significant parameters influencing the productivity. Singh and Francis [17] used Taguchi technique to find out the effect of temperature and inclination angle on the performance of the solar still. Both inclination angle and water temperature were found to be significant factors. Verma et al. [18] employed Taguchi method to establish the optimal set of parameters for passive slope solar still. The experiment concluded that water temperature and glass temperature were important for optimizing the production. Refalo et al. [19] integrated the solar chimney and condenser with the solar still, and the distillate output was increased from 4.7 to 5.11 L/m^2 d. Tanaka [20] concluded that the daily amount of distillate produced by a tilted wick solar still could be increased by using a flat plate bottom reflector. Alaudeen et al. [21] tested a single-slope solar still of glass basin with different heat storage materials in it. The percentage increase in output when corrugated sheet was used as basin material was nearly 34% higher than the conventional still. Maiti et al. [22] fitted a stepped solar still with north south reflectors in *V*-trough assembly and achieved twofold increase in distilled water production from concentrated seawater. Boodhan and Haraksingh [23] fabricated a cascade type solar still and studied the effect of different glass cover thickness and different solar still orientations on productivity. A 4.76-mm thick glass cover facing south produced the highest yield. Arjunan et al. [24] attempted to increase the productivity of a solar still by increasing temperature difference between water and glass. They used sponge liners at the inner wall surface. The optimum thickness of the sponge liner was 5 mm, and the yield was 35.2% higher than the conventional still.

2. Experimental setup

For conducting the experiment, a single-slope solar still was fabricated. The dimension of the solar still was 0.9 m × 0.7 m × 0.4 m, and it was fabricated using galvanized iron. The solar still was placed inside the wooden box, and gap between the solar still and wooden box was filled by heat resistant materials. The top of the solar still was covered by 4 mm thick glass, and it was placed at an angle of 11°. Proper arrangements were also made for collecting distilled water.

Adjacent to the solar still, a mini solar pond was constructed. Upper dimension of the solar pond was 45 cm × 45 cm. The lower dimension of the pond was 30 cm × 30 cm. The height was 150 cm. Sodium chloride mixed water was poured into the solar pond. Arrangements were made for connecting the solar still with mini solar pond at three different levels. For this purpose copper heat pipe was used. It was linked at 25 cm (lower converting zone [LCZ]), 75 cm (middle converting zone [MCZ]) and 125 (upper converting zone [UCZ]). Sodium chloride concentration in the water was varied, and the experiment was conducted at 1.5, 2.5 and 3.5 kg levels. A reflecting mirror was placed below the solar still to focus solar radiation into the basin. The angle of the mirror was adjusted at three levels: –15°, 0°and 15°. Another reflecting mirror was fitted at the top of the solar pond. The angle of the mirror was adjusted at three levels: 90°, 113° and 135°. The experimental setups used in the experiment are given in Figs. 1–5.

The experiment was conducted at Villianur, Pondicherry, India (11.9310° N, 79.7852° E). At 8.00 a.m. 6 L of water was poured into the solar still. As per the OA, the experiments were conducted. The distilled water collected was measured at 6.00 p.m., and it was recorded for further analysis.

3. Theoretical analysis

Daily efficiency of the solar still and the temperature of pond at various zones are calculated theoretically.

3.1. Energy balance equations for single-basin solar still

The energy balance equations for the basin plate, water mass and glass cover of the single-basin solar still can be written as follows.

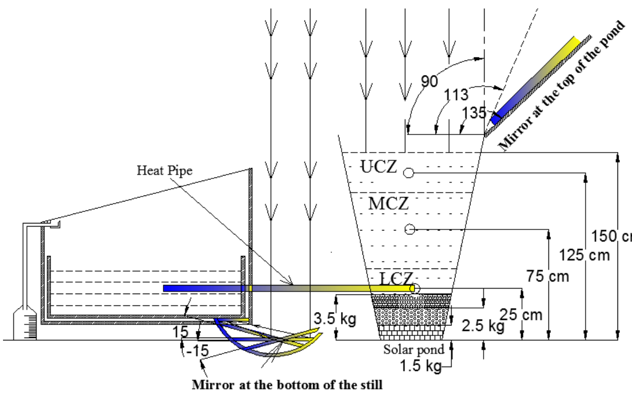

Fig. 1. Schematic diagram of the experimental setup.

3.1.1. For basin plate

The solar energy received by the basin plate ($A_b \times AB_b \times H_s$) is equal to the summation of the energy gained by the basin plate $\left(m_b \times c_{pb} \times \left(\frac{dT_b}{dt}\right)\right)$, side losses ($Q_{loss}$) and energy lost by convective heat transfer between the basin and water ($Q_{c,b-w}$) [4,5].

$$\left(A_b \times AB_b \times H_s\right) = m_b \times c_{pb} \times \left(\frac{dT_b}{\mathrm{dt}}\right) + Q_{loss} + Q_{c,b-w} \quad (1)$$

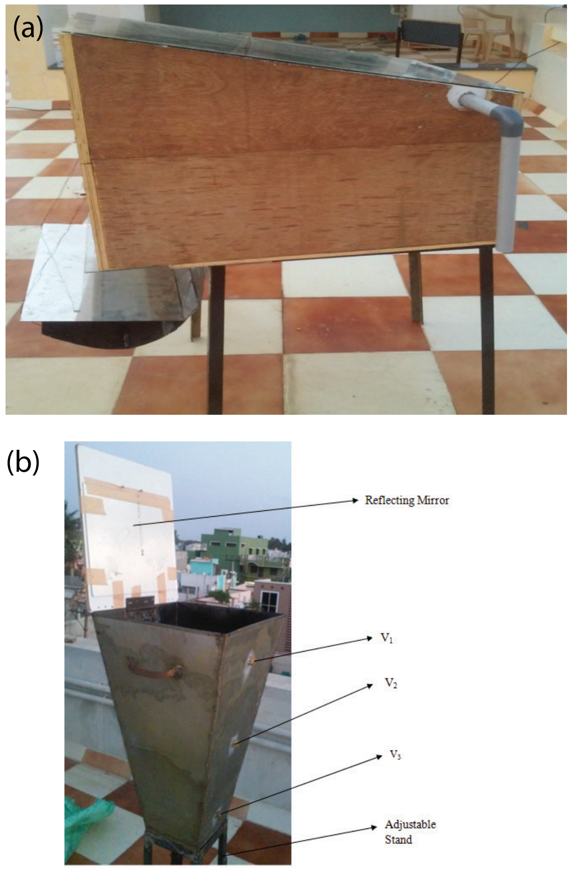

Fig. 2. (a) Solar still and (b) mini solar pond.

Fig. 3. Integration of solar still and solar pond at UCZ.

3.1.2. For water mass

The summation of the solar energy received by the water in the basin (A_w × AB_w × H_s), convective ($Q_{c,b-w}$), radiative ($Q_{r,b-w}$) heat transfer between basin and water is equal to the summation of energy lost by convective heat transfer between water and glass ($Q_{c,w-g}$), radiative heat transfer between water and glass ($Q_{r,w-g}$), evaporative heat transfer ($Q_{e,w-g}$) between water and glass and energy gained by the saline water ($m_w \times c_{pw} \times \left(\frac{dT_w}{\mathrm{d}t}\right)$) [4,5].

$$\left(A_w \times \mathrm{AB}_w \times H_s\right) + Q_{c,b-w} + Q_{r,b-w} = m_w \times c_{pw} \times \left(\frac{\mathrm{d}T_w}{dt}\right) + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} \tag{2}$$

3.1.3. For glass cover

The summation of solar energy gained by the glass cover from sun (A_g × AB_g × H_s), convective ($Q_{c,w-g}$), evaporative ($Q_{e,w-g}$) and radiative ($Q_{r,w-g}$) heat transfer from water to glass is equal to the summation of energy lost by radiative heat transfer between glass and sky ($Q_{r,g\text{–sky}}$), convective heat transfer between glass and sky ($Q_{c,g\text{–sky}}$), evaporative heat transfer between glass and sky ($Q_{e,g\text{–sky}}$) and energy gained by glass $\left(m_g \times c_{pg} \times \left(\frac{\mathrm{d}T_g}{\mathrm{d}t}\right)\right)$ [4,5].

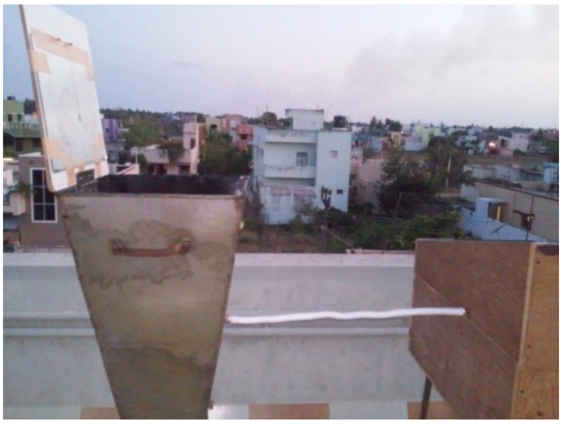

Fig. 4. Integration of solar still and solar pond at MCZ.

Fig. 5. Integration of solar still and solar pond at LCZ.

$$(A_g \times \mathrm{AB}_g \times H_s) + Q_{c,w-g} + Q_{e,w-g} + Q_{r,w-g} = m_g \times c_{pg} \times \left(\frac{\mathrm{d}T_g}{\mathrm{d}t}\right) + Q_{c,g-\mathrm{sky}} + Q_{r,g-\mathrm{sky}} + Q_{e,g-\mathrm{sky}} \tag{3}$$

3.2. Calculation of absorption values (AB)

The absorption value for glass cover can be written as:

$$\mathrm{AB}_g = \alpha_g(1-\rho_g) \tag{4}$$

The absorption value for water mass can be written as:

$$\mathrm{AB}_w = \alpha_w(1-\rho_g-\mathrm{AB}_g) \tag{5}$$

The absorption value for basin plate can be written as:

$$\mathrm{AB}_b = \alpha_g(1-\rho_g-\mathrm{AB}_g-\mathrm{AB}_w) \tag{6}$$

Initially the water temperature, basin temperature and upper, lower glass temperature are taken as ambient temperature. The change in water temperature ($\mathrm{d}t_w$), basin temperature ($\mathrm{d}t_b$) and glass temperature ($\mathrm{d}t_g$) are noted.

For next time, the parameters are redefined as:

$$T_w = T_w + \mathrm{d}T_w \tag{7}$$

$$T_g = T_g + \mathrm{d}T_g \tag{8}$$

$$T_b = T_b + \mathrm{d}T_b \tag{9}$$

These values are substituted in Eqs. (1)–(3). By using the MATLAB program, the corresponding equations are solved.

The transient energy gained by the single-basin solar still = the energy rise from direct heating of sun + the energy received from pond.

3.3. Calculation of productivity

$$m_e = \frac{Q_{e,w-g} \times (T_w - T_g)}{h_{fg}} \tag{10}$$

The total day production of single-basin solar still is given by:

$$M_e = \sum_8^{18} m_e$$

3.4. Daily efficiency

The daily efficiency of the single-basin still is expressed as:

$$\eta = \frac{M_e h_{fg}}{A_b \times \Delta T \times \sum H_s} \times 100 \tag{11}$$

The different parameters used in the above equations (Eqs. (1)–(11)) are calculated using the formulas given in

Table 1
Parameters used for theoretical study

S. No.	Various parameter used	Values
1	Mass of basin (m_b)	9 kg
2	Mass of water (m_w)	6 kg
3	Mass of glass (m_g)	7 kg
4	Area of water (A_w)	0.63 m^2
5	Area of basin (A_b)	0.63 m^2
6	Area of glass (A_g)	0.96 m^2
7	Absorptivity of basin (α_b)	0.97
8	Absorptivity of water (α_w)	0.04
9	Absorptivity of glass (α_g)	0.047
10	Reflectivity of the glass (ρ_g)	0.09
11	Specific heat of basin (Cp_b)	471 J/kg °C
12	Specific heat of glass (Cp_g)	799 J/kg °C
13	Heat loss coefficient from basin to ambient (U_b)	14 W/m^{2}K
14	Convective heat transfer between basin and water	131 W/m^{2}K
15	Convective heat transfer between glass and water	96 W/m^{2}K

Appendix 1. Also the various thermophysical values used for calculation purpose are shown in Table 1.

4. Design of experiment

Four variables (parameters) that were influencing the performance of the solar still were selected. Further three levels of the parameters were identified. The four parameters and three levels that were taken up for study in the experiment are given in Table 2.

For the present study, we have chosen four parameters only. Besides these four parameters, there are many other parameters too that play a crucial role in the process of optimization. But, we vary only the selected four parameters and keep all other parameters constant.

5. Results and discussion

To determine the best performing levels of the four parameters at three levels $L_{27}3^4$ OA was selected. Six liters of water was poured into the solar still. The experiment was conducted as per the OA selected. The distillate yield of the experiments was observed and recorded. The OA and results are given in Appendix 2.

5.1. S/N ratios

S/N ratio was calculated for the result of the experiment. Our objective was to maximize the performance of the solar still. So, larger the best method was used. For the calculation of S/N ratio the following formula was used:

Table 2
Parameters and their levels

S. No.	Parameters	Level 1	Level 2	Level 3
1	Concentration of sodium chloride (kg)	1.5	2.5	3.5
2	Mini solar pond zones (cm)	25 (LCZ)	75 (MCZ)	125 (UCZ)
3	Angle of the mirror at the bottom of the solar still (°)	–15°	0°	15°
4	Angle of the mirror at the top of the pond (°)	90°	113°	135°

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=0}^{n}\frac{1}{y^2}\right)$$

where Y is the value of output and n is the number of outputs ($n = 2$).

S/N ratios for different levels of parameters are given in Table 3. S/N ratios reveal the contribution of parameters at different levels to the performances of solar still. The following levels of the selected parameters are recommended and they are shown in Table 4.

If we combine level 3 of parameter I, level 1 of parameter II, level 2 of parameter III and level 3 of parameter IV, the performance is optimum. Among the four parameters, the parameter II (solar pond zone) was considered to be the most significant contributor to the performance of the solar still. The next important significant contributor was parameter I (concentration of sodium chloride). Parameter III (angle of the mirror at the bottom of the still) was the third contributor. The fourth contributor was parameter IV (angle of the mirror at the top of the pond).

5.2. Mean performance of parameters

Mean performance of parameters at different levels is given in Table 5.

Level 1 of parameter II (mini solar pond zones) was the significant contributor. The next significant contributor was level 3 of parameter I (concentration of sodium chloride). Level 2 of parameter III (angle of the mirror at the bottom of the still) and level 3 of parameter IV (angle of the mirror at the top of the pond) occupied the fourth and third place. The best performing levels of parameters and their mean performance levels are given in Table 6.

The mean values for level 3 of parameter I, level 1 of parameter II, level 2 of parameter III and level 3 of parameter IV are the highest. So a combination of these levels yields the best performance.

5.3. Graphical representation of mean effect

The mean effect of the four parameters is depicted in Fig. 6.

Fig. 6.1 explains that as the sodium chloride concentration increased, the performance was also increased. In Fig. 6.2, it is explained that the performance of the solar still was the best when it was linked with LCZ. Fig. 6.3 shows that as the angle of mirror at the bottom of the still increased from –15° to 0° the performance also improved. Further increase in the angle decreased the performance. Fig. 6.4 explains that when the mirror was placed at 135° above the solar pond, the performance was high.

5.4. Variation in the performance

The standard deviation (SD) explains the consistency in the performance of the parameters. The SDs of the performance of the parameters are given in Table 7.

The SDs for level 3 of parameter I, level 1 of parameter II, level 2 of parameter III and level 2 of parameter IV are the lowest. The SD for the best performing levels of the four parameters are low. This explains the consistency in the performance of the best performing levels. The same phenomenon is explained in Fig. 7.

5.5. Analysis using ANOVA

The experimental results were also analyzed using ANOVA technique. They are given in Table 8.

H_0 is the selected four parameters that have no significant influence in the performance of solar still.

The calculated F values are compared with the p value. This shows that the two parameters (concentration of sodium chloride and solar pond zones) significantly contributed to the performance of the solar still. The S/N ratio analysis also confirms this result. The other two parameters, i.e., angle of the mirror at the bottom of the still and angle of the mirror at the top of the pond are the third and fourth significant contributors.

5.6. Regression analysis

Regression analysis explains the nature of relationship between independent variables (X) and dependent variable (Y). In this experiment, the concentration of sodium chloride (X_1), mini solar pond zones (X_2), angle of the mirror at the bottom of the solar still (X_3) and angle of the mirror at the top of the pond (X_4) were taken as independent variables and performance of the solar still (Y) was taken as the dependent variable. The following regression equation explains the mathematical relationship between the variables.

5.7. Regression equation

$$Y = 2.943 + 0.2278X_1 - 0.01367X_2 + 0.00000X_3 + 0.00195X_4$$

where X_1 is the concentration of sodium chloride, X_2 is the mini solar pond zones, X_3 is the angle of the mirror at the bottom of the solar still and X_4 is the angle of the mirror at the top of the pond.

Table 3
S/N ratios for the different level of parameters

S. No.	Concentration of sodium chloride (kg)	Mini solar pond zones (cm)	Angle of the mirror at the bottom of the solar still (°)	Angle of the mirror at the top of the pond (°)
1	7.514	10.589	8.152	8.385
2	8.370	8.350	8.581	8.146
3	9.086	6.031	8.238	8.440
Delta	1.572	4.558	0.429	0.295
Rank	2	1	4	3

Table 4
Best performing parameter level

S. No.	Parameters	Best performing level
1	Concentration of sodium chloride (kg)	3 – (3.5 kg)
2	Mini solar pond zones (cm)	1 – (25 cm)
3	Angle of the mirror at the bottom of the solar still (°)	2 – (0°)
4	Angle of the mirror at the top of the pond (°)	3 – (135°)

Table 5
Means for the different level of parameters

Level	Concentration of sodium chloride (kg)	Mini solar pond zones (cm)	Angle of the mirror at the bottom of the solar still (°)	Angle of the mirror at the top of the pond (°)
1	2.444	3.389	2.656	2.661
2	2.683	2.633	2.739	2.633
3	2.906	2.011	2.639	2.739
Delta	0.461	1.378	0.100	0.106
Rank	2	1	4	3

Significance of the regression coefficients are tested with the help of *t*-test. This is shown in Table 9. At 5% level, the parameters I and II have significant influence on the performance of solar still. Regression coefficient for sodium chloride concentration is 0.2278. This explains that as sodium chloride concentration increased, the performance of the solar still also increased. On the other hand, the regression coefficient of mini solar pond zone is –0.01367. This explains that as the height of the solar pond at which the solar still was linked increased, the performance of solar still declined. In other words, the linking of the solar still with LCZ increased the performance.

The regression coefficients for different levels of parameters are given in Table 10. The regression coefficient for sodium chloride concentration levels at 2.5 and 3.5 kg are positive. This shows that these two levels of parameter I influence the performance of solar still. But sodium chloride concentration level at 3.5 kg had the most significant influence in the performance of the solar still. For parameter II the regression coefficient is positive only for level 1. This shows that linking of solar still with LCZ of the solar pond alone positively influenced the performance of the solar still. In the same manner level 2 of parameter III (angle of the mirror at the bottom of the solar still at 0°) and level 3 of parameter IV (angle of the mirror at the top of the pond at 135°) were positively influencing the performance. The S/N ratio analysis also confirms the above results.

Table 6
Best performing parameter level (mean level)

S. No.	Parameters	Level	Mean performing level
1	Concentration of sodium chloride (kg)	3	2.0906
2	Mini solar pond zones (cm)	1	3.389
3	Angle of the mirror at the bottom of the solar still (°)	2	2.739
4	Angle of the mirror at the top of the pond (°)	3	2.739

5.8. Experiment by combining best performing levels

The Taguchi method prescribed the best performing levels of the four parameters. By combining these best performing levels, the experiment was conducted. The experiment was repeated for 7 d, and the average performance was obtained. This is shown in Table 11.

The temperature recorded at 3.00 p.m. on the day of experiment was taken as the maximum temperature of the day. In the same manner water temperature and glass temperature were also recorded at 3.00 p.m. and taken as the maximum temperature. The experiment was started at 8.00 a.m. Six liters of water was poured into the still. The output of water collected was recorded every 2 h.

The maximum ambient temperature ranged between 36°C and 39°C. The maximum average glass temperature reached was 79°C and the average maximum water temperature reached was 83°C. As a result, the average output of water collected in one experiment day was 3.26 L. In other words average daily efficiency reached was 54.29%.

5.9. Distribution of output in a day

The experiment was started at 8.00 a.m. and continued up to 6.00 p.m. The output was measured at the end of every 2 h and it was recorded. The distribution of output in a day from 8.00 a.m. to 6.00 p.m. is given in Table 12.

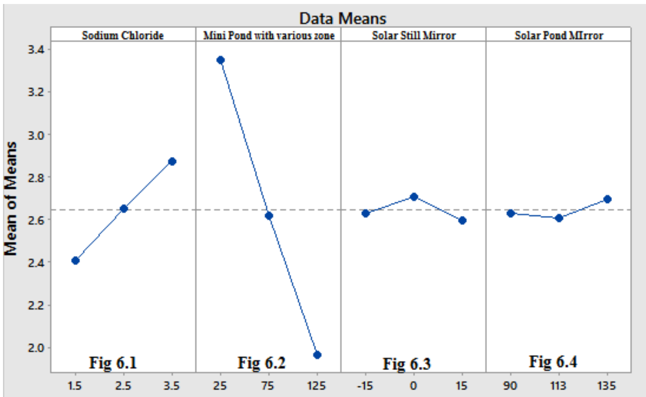

Fig. 6. Parameter levels and their means.

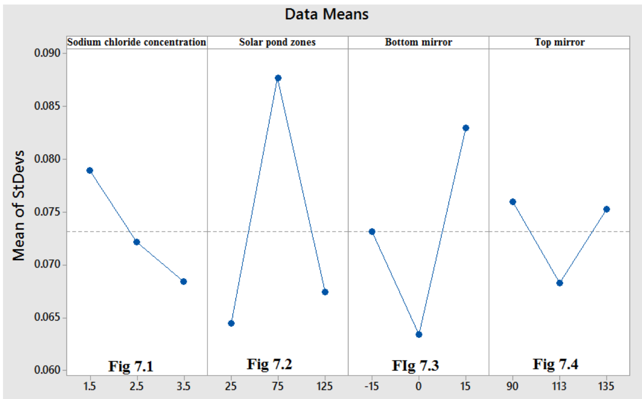

Fig. 7. Standard deviation for parameters levels.

Table 7
Standard deviations for the different level of parameters

Level	Concentration of sodium chloride (kg)	Mini solar pond zones (cm)	Angle of the mirror at the bottom of the solar still (°)	Angle of the mirror at the top of the pond (°)
1	0.07895	0.06443	0.07316	0.07599
2	0.07212	0.08768	0.06339	0.06824
3	0.06844	0.06740	0.08296	0.07528

Between 8.00 a.m. and 10 a.m. the production was very low. From 10.00 a.m. to 2.00 p.m. the production improved. After 2.00 p.m. the production declined. The maximum production was between 12.00 p.m. and 2.00 p.m. Between 8.00 a.m. and 10.00 a.m. and between 4.00 p.m. and 6.00 p.m. the output was low.

The average performance during every 2 h is given in Fig. 8. The performance of the solar still increased up to 2 p.m. and then it declined. Nearly, 60% of the output was produced between 12.00 p.m. and 4.00 p.m.

5.10. Comparison between theoretical and experimental values

A comparison is made between theoretical value and experimental results and there was close agreement between

Table 8
Analysis of variances

Source	DF	Adj. SS	Adj. MS	*F* value	*p* Value
Concentration of sodium chloride	2	0.98074	0.49037	110.33	0.000
Mini solar pond zones	2	8.68963	4.34481	977.58	0.000
Angle of the mirror at the bottom of the solar still	2	0.05852	0.02926	6.58	0.007
Angle of the mirror at the top of the pond	2	0.03852	0.01926	4.33	0.029
Error	18	0.08000	0.00444		
Total	26	9.84741			

Table 9
Regression coefficients of parameters

Term	Coefficient	SE coefficient	*t* Value	*p* Value	VIF
Constant	2.943	0.146	20.22	0.000	
Concentration of sodium chloride	0.2278	0.0249	9.16	0.000	1.00
Mini solar pond zones	–0.01367	0.000497	–27.47	0.000	1.00
Angle of the mirror at the bottom of the solar still	0.00000	0.00166	0.00	1.000	1.00
Angle of the mirror at the top of the pond	0.00195	0.00111	1.76	0.092	1.00

Table 10
Regression coefficients of different levels of parameters

Term	Coefficient	SE coefficient	*t* Value	*p* Value	VIF
Constant	2.7074	0.0148	182.75	0.000	
Concentration of sodium chloride					
1.5	–0.2296	0.0210	–10.96	0.000	1.33
2.5	0.0037	0.0210	0.18	0.862	1.33
3.5	0.2259	0.0210	10.78	0.000	*
Mini solar pond zones					
25	0.7148	0.0210	34.12	0.000	1.33
75	–0.0630	0.0210	–3.01	0.008	1.33
125	–0.6519	0.0210	–31.11	0.000	*
Angle of the mirror at the bottom of the solar still					
–15	–0.0296	0.0210	–1.41	0.174	1.33
0	0.0593	0.0210	2.83	0.011	1.33
15	–0.0296	0.0210	–1.41	0.174	*
Angle of the mirror at the top of the pond					
90	–0.0185	0.0210	–0.88	0.388	1.33
113	–0.0519	0.0210	–2.47	0.024	1.33
135	0.0704	0.0210	3.36	0.003	*

Note: * — level 3 in each parameter has no value.

the two. The experimental value is lower than the theoretical value by 6.43%. The gap between the two, ranges between 4% and 9% only. This is shown in Table 13.

The theoretical daily efficiency value and experimental daily efficiency are given in Fig. 9. The basin glass cover temperature, basin water temperature, and temperatures of mini solar pond at UCZ, MCZ and LCZ at different ambient temperatures were theoretically calculated. They were compared with experimental values. This is shown in Fig. 10.

5.11. Chemical analysis of input water and distilled water

A chemical analysis was made between the initial water used in the experiment and the distilled water produced. The characteristics of the two are recorded in Table 14. The pH value, water hardness, electrical conductivity (EC) and total dissolved salt (TDS) values of the distilled water are much lower than the initial water used and they are within the acceptable limits.

5.12. Comparison between conventional still and modified still

The performance of the solar pond linked modified solar still was compared with the conventional still (without modification). This is given in Table 15. The average performance of the modified solar still was 95.54% higher than the conventional still. The performance of these two stills at different time intervals is given in Fig. 11. Along with this, the percentage increase in the efficiency of the modified solar still is also given in the same figure.

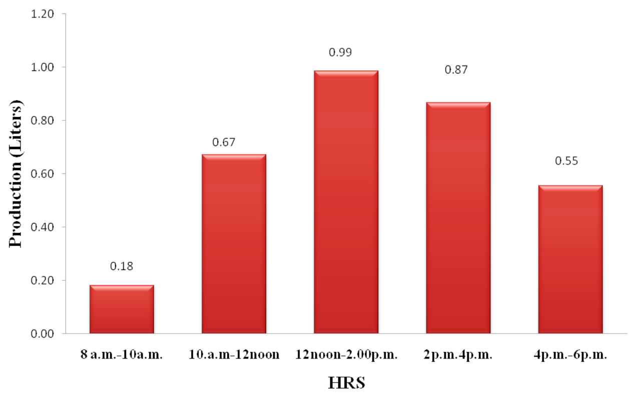

Fig. 8. Performance at different time intervals.

Table 11
Efficiency levels

S. No.	Date	Maximum temperature (°C)	Glass temperature (°C)	Water temperature (°C)	Input water (L/d)	Output after 10 h (L/d)	Daily efficiency (%)
1	02.05.2016	36	75	79	6	3	50
2	03.05.2016	37	78	80	6	3.2	53
3	04.05.2016	38	78	81	6	3.1	52
4	05.05.2016	38	79	83	6	3.5	58
5	06.05.2016	39	79	82	6	3.6	60
6	07.05.2016	38	77	80	6	3.0	50
7	08.05.2016	38	78	82	6	3.4	57
Average			78	81	6	3.26	54.29

Table 12
Distribution of output in a day

Date	Output (L/d)					
	8 a.m.–10 a.m. (h)	10 a.m.–12 p.m. (h)	12 p.m.–2 p.m. (h)	2 p.m.–4 p.m. (h)	4 p.m.–6 p.m. (h)	Total
02.05.2016	0.15	0.60	0.96	0.75	0.54	3
03.05.2016	0.16	0.64	0.96	0.96	0.48	3.2
04.05.2016	0.31	0.62	0.93	0.62	0.62	3.1
05.05.2016	0.14	0.77	1.05	0.98	0.56	3.5
06.05.2016	0.18	0.72	1.08	0.9	0.72	3.6
07.05.2016	0.15	0.66	0.9	0.84	0.45	3
08.05.2016	0.17	0.68	1.02	1.02	0.51	3.4
Average	0.18	0.67	0.99	0.87	0.55	3.26

Table 13
Comparison of theoretical value and experimental value

S. No.	Date	Ambient temperature (°C)	Daily efficiency (%)		Gap (%)
			Experimental	Theoretical	
1	02.05.2016	36	50	57	7
2	03.05.2016	37	53	59	6
3	04.05.2016	38	52	57	5
4	05.05.2016	38	58	63	5
5	06.05.2016	39	60	69	9
6	07.05.2016	38	50	59	9
7	08.05.2016	38	57	61	4
Average			54.29	60.71	6.43

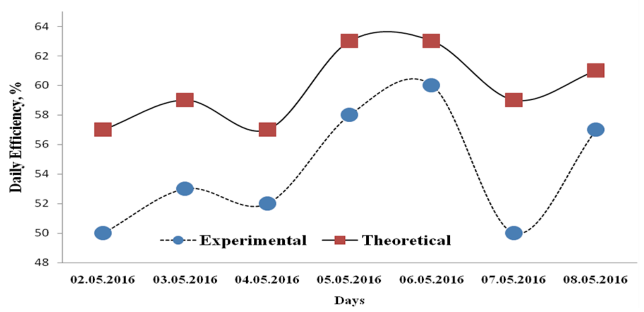

Fig. 9. Comparison between theoretical value and experimental result.

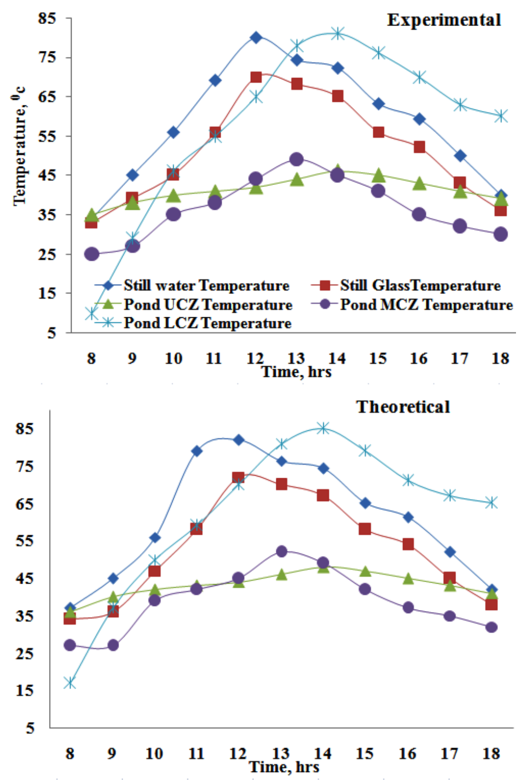

Fig. 10. Variation in temperature of glass cover, basin water and the different zones of pond.

Table 14
Comparative analysis of samples

Sample	pH	Total hardness (mg/L)	EC (S/m)	TDS (mg/L)
Raw water samples	10.11	780	67	1,300
Distilled water samples	5.55	13	0	23

6. Conclusion

The objective of this study was to maximize the performance of the solar still. For this purpose the solar still was linked with mini solar pond. Mirror was fitted on the solar pond and additional solar radiation was focused into the pond. Further with the help of mirror solar rays were focused into the still through the bottom of the basin. Four parameters were identified as influencing the distillate output of this still. They were: the sodium chloride concentration level of pond water, the zone with which the still was linked, the inclination angle of the mirror fitted in the pond and the inclination angle of mirror used to focus solar rays into the still. Three levels of the above four parameters were selected. The experiment was conducted on the basis of the selected OA. Taguchi method was used to identify the best performing levels of the four parameters. After conducting the experiment, the S/N ratios for different levels of the parameters were calculated. Sodium chloride concentration level of 3.5 kg, LCZ of the solar pond, inclination angle of 0° of the mirror used for focusing solar radiation into the still and inclination angle of 135° of the mirror used in solar pond had the highest S/N ratios of 9.086, 10.589, 8.581 and 8.44, respectively. The mean performance of the above four levels were 2.906, 3.389, 2.739 and 2.739, respectively. They were the highest, compared with other levels. The regression coefficient for the above four levels was positive. This shows that they significantly influenced the performance. So the performance of the solar still can be optimized by linking the solar still with LCZ of the solar pond, increasing the sodium chloride concentration level to 3.5 kg, keeping the inclination angle of the mirror at the pond at 135° and focusing solar rays through the base of the still by fitting a mirror at an inclination angle of 0°.

Table 15
Comparison between conventional and modified still

S. No.	Date	Ambient temperature (°C)	Conventional still yield (kg)	Still with pond yield (kg)	Daily efficiency rise (%)
1	02.05.16	36	1.5	3	100.00
2	03.05.16	37	1.7	3.2	88.24
3	04.05.16	38	1.7	3.1	82.35
4	05.05.16	38	1.8	3.5	94.44
5	06.05.16	39	1.9	3.6	89.47
6	07.05.16	38	1.4	3	114.29
7	08.05.16	38	1.7	3.4	100.00
Average			1.9	3.26	95.54

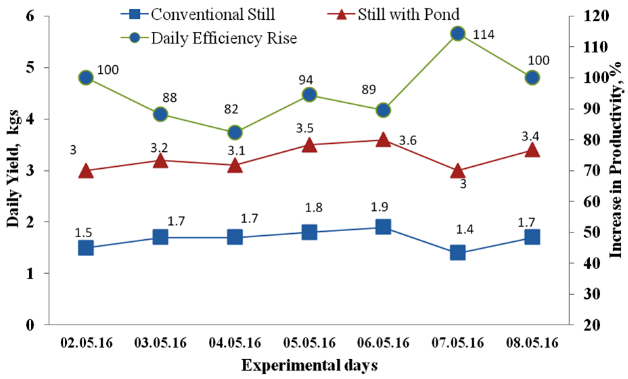

Fig. 11. Comparison of daily yield and productivity rise.

By combining the best performing levels of the above four parameters, the experiment was conducted using the solar pond linked still. As a result the distillate output collected in one experiment day was 3.26 L. The daily efficiency achieved was 54.29%. Compared with the conventional still, the performance was higher by 95.54%. The distillate output was recorded for every 2 h. The distillate yield was low from 8 a.m. to 10 a.m. The maximum production was obtained between 12 p.m. and 2 p.m. Nearly, 60% of the yield was produced between 12 p.m. and 4 p.m.

To conclude, Taguchi method is best suited to select the best performing levels of parameters that influence distillate output. This will enable us to attain the optimum performance level.

Symbols

A — Area, m^2
AB — Absorption (with indices for different surfaces)
c_p — Specific heat capacity, J/kg °C
H — Solar intensity, W/m^2
m — Mass, kg
h — Heat transfer coefficient, W/m °C
P — Partial pressure, N/m
Q — Heat transfer rate, W
T — Temperature, °C
U_b — Heat loss coefficient from basin to ambient, W/m^2°C
h_{fg} — Latent heat of water, J/kg K
V — Wind velocity, m/s
dT — Temperature difference, °C
dt — Differential time, s
UCZ — Upper converting zone
MCZ — Middle converting zone
LCZ — lower converting zone
S/N — Signal-to-noise ratio
SD — Standard deviation
M_e — Daily condensate
K_w — Thermal conductivity, W/m K
L — Length of pond, m
$h(z)$ — Solar radiation penetrating depth z in the pond

Greek

α — Absorptivity
σ — Stefan–Boltzmann constant (5.6697×10^{-8} W/m^2 K^4)
Δ — Difference
ε — Emissivity
η — Daily productivity

Subscripts

a — Ambient air
b — Basin
c — Convection
e — Evaporation
g — Glass
loss — Side loss
r — Radiation
w — Water
ANOVA — Analysis of variance
DF — Degrees of Freedom
SS — Sum of Squares
MS — Mean square
SE — Standard Error
VIF — Variance Inflation Factor

References

[1] A.A. El-Sebaii, M.R.I. Ramadan, S. Aboul-Enein, N. Salem, Thermal performance of a single-basin solar still integrated with a shallow solar pond, Energy Convers. Manage., 49 (2008) 2839–2848.

[2] M. Appadurai, V. Velmurugan, Performance analysis of fin type solar still integrated with fin type mini solar pond, Sustain. Energy Technol. Assess., 9 (2015) 30–36.

[3] P. Malaiyappan, N. Elumalai, Asymmetrical solar still coupled with the mini solar pond: performance evaluation on clear, partially cloudy and cloudy days, Appl. Mech. Mater., 787 (2015) 22–26.

[4] V. Velmurugan, K. Srithar, Solar stills integrated with a mini solar pond — analytical simulation and experimental validation, Desalination, 216 (2007) 232–241.

[5] V. Velmurugan, J. Mandlin, B. Stalin, K. Srithar, Augmentation of saline streams in solar stills integrating with a mini solar pond, Desalination, 249 (2009) 143–149.

[6] V. Velmurugan, K. Srithar, Prospects and scopes of solar pond: a detailed review, Renew. Sustain. Energy Rev., 12 (2008) 2253–2263.

[7] A. Tamini, Performance of a *solar* still with reflectors and black dye, Sol. Wind Technol., 4 (1987) 443–446.

[8] I. Al-Hayek, O.O. Badran, The effect of using different designs of solar stills on water distillation, Desalination, 169 (2004) 121–127.

[9] M.E. El-Swify, M.Z. Metias, Performance of double exposure solar still, Renew. Energy, 26 (2002) 531–547.

[10] P. Prakash, V. Velmurugan, Experimental analysis of a solar still with reflectors and sensible heat storage mediums, Appl. Mech. Mater., 787 (2015) 107–111.

[11] H. Tanaka, Experimental study of a basin type solar still with internal and external reflectors in winter, Desalination, 249 (2009) 130–134.

[12] Z.M. Omara, A.E. Kabeel, M.M. Younes, Enhancing the stepped solar still performance using internal and external reflectors, Energy Convers. Manage., 78 (2014) 876–881.

[13] S. Abdallah, O. Badran, M.M. Abu-Khader, Performance evaluation of a modified design of single slope solar still, Desalination, 219 (2008) 222–230.

[14] Z.M. Omara, A.E. Kabeel, M.M. Younes, Enhancing the stepped solar still performance using internal reflectors, Desalination, 314 (2013) 67–72.

[15] H. Tanaka, Monthly optimum inclination of glass cover and external reflector of a basin type solar still with internal and external reflectors, Sol. Energy, 84 (2010) 1959–1966.

[16] P. Gupta, N. Singh, Investigation of the effect of process parameters on the productivity of single slope solar still: a Taguchi approach, Int. J. Curr. Eng. Technol., 4 (2015) 320–322.

[17] N. Singh, V. Francis, Investigating the effect of water temperature and inclination angle on the performance of single slope solar still: a Taguchi approach, Int. J. Eng. Res. Appl., 3 (2013) 404–407.

[18] V.K. Verma, I.S. Rout, A.K. Rai, A. Gaikwad, Optimization of parameters affecting the performance of passive solar distillation system by using Taguchi method, IOSR J. Mech. Civil Eng., 7 (2013) 37–42.

[19] P. Refalo, R. Ghirlando, S. Abela, The use of a solar chimney and condensers to enhance the productivity of a solar still, Desal. Wat. Treat., 8 (2015) 1–14.

[20] H. Tanaka, Optimum inclination of still and bottom reflector for tilted wick solar still with flat plate bottom reflector, Desal. Wat. Treat., 51 (2013) 6482–6489.

[21] A. Alaudeen, S.A. Abu Thahir, K. Vasanth, M.I.A. Tom, K. Srithar, Experimental and theoretical analysis of solar still with glass basin, Desal. Wat. Treat., 54 (2015) 1489–1498.

[22] S. Maiti, C. Bhatt, P. Patel, P.K. Ghosh, Practical and sustainable household seawater desalination using an improved solar still, Desal. Wat. Treat., 57 (2016) 3358–3371.

[23] M.K. Boodhan, I. Haraksingh, An investigation into the effect on the productivity of cascade-type solar distillation systems with varying cover thicknesses and still orientations under tropical Caribbean climatic conditions, Desal. Wat. Treat., 55 (2015) 3295–3302.

[24] T.V. Arjunan, H.S. Aybar, N. Nedunchezhian, Effect of sponge liner on the internal heat transfer coefficients in a simple solar still, Desal. Wat. Treat., 29 (2011) 271–284.

Appendix 1

The following equations are used for the theoretical calculation. They are referred from references [4,5].

For single-basin still:

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

$$Q_{\text{loss}} = U_b \times A_b \times (T_b - T_{\text{sky}})$$

$$Q_{c,w-g} = h_{c,w-g} \times A_w \times (T_w - T_g)$$

$$h_{c,w-g} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{0.2665 \times 10^3 - P_w}\right]^{1/3}$$

$$Q_{r,w-g} = h_{r,w-g} \times A_w \times (T_w - T_g)$$

$$h_{r,w-g} = \varepsilon_{eff} \times \sigma \times 0.999\left[\frac{(T_w + 273.12)^4 - (T_g + 273.12)^4}{(T_w - T_g)}\right]$$

$$Q_{e,w-g} = h_{e,w-g} \times A_w \times (T_w - T_g)$$

$$h_{e,w-g} = \frac{M_{w1} \times h_{fg} \times p_t}{M_a \times c_{pa}(p_t - p_w)(p_t - p_g)} h_{c,w-g}$$

$$Q_{r,g-\text{sky}} = \varepsilon_g \times A_g \times \left[(T_g + 273.12)^4 - (T_{\text{sky}} + 273.12)^4\right]$$

$$Q_{c,g-\text{sky}} = h_{c,g-\text{sky}} \times A_g \times (T_g - T_{\text{sky}})$$

$$h_{c,g-\text{sky}} = 2.9 + 3V$$

$$\epsilon_{\text{eff}} = \left(\frac{1}{\epsilon_{\text{ug}}} + \frac{1}{\epsilon_{\text{lg}}} - 1\right)^{-1}$$

$$T_{\text{sky}} = T_a - 6$$

$$T_{\text{LCZ}} = \frac{A_s\left[h(z)H_s + \dfrac{K_w T_a}{L_{\text{mcz}}}\right]}{\left[\left(\dfrac{m_p c_p}{\text{dt}}\right) + \left(\dfrac{A_p k_w}{L_{\text{mcz}}}\right)\right]}$$

$$T_{\text{MCZ}} = \frac{A_s\left[h(z)H_s + \dfrac{K_w T_a}{L_{\text{ucz}}}\right]}{\left[\left(\dfrac{m_p c_p}{\text{dt}}\right) + \left(\dfrac{A_p k_w}{L_{\text{ucz}}}\right)\right]}$$

$$T_{\text{UCZ}} = \frac{A_s\left[h(z)H_S + \dfrac{K_w T_a}{L_{\text{upper}}}\right]}{\left[\left(\dfrac{m_p c_p}{\text{dt}}\right) + \left(\dfrac{A_p k_w}{L_{\text{upper}}}\right)\right]}$$

$$T_w = \frac{(h_{c,g-\text{sky}} + h_{c,g-w})T_b - (AB_w H_s) - (h_{c,g-\text{sky}} T_a)}{h_{c,g-w}}$$

$$T_g = \frac{(\text{AB}_g H_S) + (h_{c,g-w} T_w) + (h_{c,w-b} T_w)}{(h_{c,w-b} + h_{c,g-w})}$$

$$P = 7235 - 431.45 T_w + 10.76 T_w^{\ 2}$$

$$h_{fg} = (2503.4 - 2.398 T_W)1000$$

Appendix 2

$L_{27}3^4$ Orthogonal array

S. No.	Concentration of sodium chloride (kg)	Mini solar pond zones (cm)	Angle of the mirror at the bottom of the solar still (°)	Angle of the mirror at the top of the pond (°)	Output 1 (L/d)	Output 2 (L/d)	S/N ratios	Mean
1	1.5	25	0	90	3.1	3.2	7.99	3.15
2	1.5	25	0	90	3.2	3.2	8.06	3.2
3	1.5	25	0	90	3.2	3.3	8.13	3.25
4	1.5	75	15	113	2.4	2.4	6.81	2.4
5	1.5	75	15	113	2.2	2.2	6.43	2.2
6	1.5	75	15	113	2.3	2.4	6.72	2.35
7	1.5	125	–15	135	1.7	1.8	5.44	1.75
8	1.5	125	–15	135	1.8	1.9	5.68	1.85
9	1.5	125	–15	135	1.8	1.9	5.68	1.85
10	2.5	25	15	135	3.4	3.5	8.39	3.45
11	2.5	25	15	135	3.4	3.5	8.39	3.45
12	2.5	25	15	135	3.3	3.4	8.26	3.35
13	2.5	75	–15	90	2.5	2.5	6.99	2.5
14	2.5	75	–15	90	2.6	2.6	7.16	2.6
15	2.5	75	–15	90	2.7	2.7	7.32	2.7
16	2.5	125	0	113	2	2.1	6.13	2.05
17	2.5	125	0	113	2	2	6.02	2
18	2.5	125	0	113	2	2.1	6.13	2.05
19	3.5	25	–15	113	3.5	3.6	8.51	3.55
20	3.5	25	–15	113	3.5	3.6	8.51	3.55
21	3.5	25	–15	113	3.6	3.5	8.51	3.55
22	3.5	75	0	135	2.9	2.9	7.63	2.9
23	3.5	75	0	135	3	3	7.78	3
24	3.5	75	0	135	3	3.1	7.85	3.05
25	3.5	125	15	90	2.2	2.3	6.53	2.25
26	3.5	125	15	90	2.1	2.2	6.33	2.15
27	3.5	125	15	90	2.1	2.2	6.33	2.15