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Enhancing solar still productivity by optimizing operational parameters

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ABSTRACT

This study aimed at enhancing the distillate production in the conventional solar still by incorporating modifications in four operational parameters-compartmental basin (*A*), basin water depth (*B*), size (diameter) of cylindrical wicks (*C*) and thickness of basin glass cover (*D*). The objective was to identify the combination of parameter levels that optimize/maximize the distillate yield using Taguchi method. For each parameter, four parameter levels were selected. The parameter levels were combined as per L_{16} orthogonal array and experiments were conducted. The experimental findings were analyzed using S/N ratio analysis, mean response method, analysis of variance and regression analysis. The parameter levels identified for optimizing production were – 100 compartments in the still basin, 20 mm basin water depth, 30 mm size wick and 4 mm thick basin glass cover. The most significant contributor (parameter) to distillate production was basin water depth (48.5%) followed by wicks (29.4%) and number of compartments in the basin (20.6%). The regression analysis revealed that as the basin water depth decreases, the yield increases. The increase in the number of compartments and the size of wicks increase the yield. Incorporating the identified parameter levels, robust design solar still was fabricated and the production was experimentally determined. The optimum production was estimated using mean response method and regression analysis. The optimum production estimated was 5,934 mL/m^2 d. But the experimental production obtained was 5,280 mL/m^2 d and it was 82% of the estimated optimum production.

Keywords: Taguchi method; S/N ratio; Mean response; Regression analysis; Optimum production

1. Introduction

Safe and clean potable water is the basic necessity of human beings along with food and air. For the survival and continuation of human race, water is essential. The agricultural development and industrial development also depend on the availability of fresh water. We get water from ponds, lakes, rivers and underground water reservoirs. The rapid growth of population and fast industrialization in the economy have resulted in a tremendous increase in the demand for fresh water. Nowadays, water is polluted beyond tolerable level. Even sacred river water of Ganges is unfit for human consumption. Pure and potable water can be produced from brackish/saline water through distillation and desalination. Two major technologies that are available for desalination of saline water are – phase change or thermal technology and single phase or membrane technology. Based on the above two technologies many desalination methods are available. The energy requirement of the above methods is more. So, in many places solar stills are used. It is a suitable technology for underdeveloped countries

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especially in arid and semi-arid regions. solar stills are easy to fabricate, and the operation and maintenance cost is low. Solar energy is the only energy required to operate the still and it is cost free and available throughout the year. It is environment friendly also. The greatest drawback of solar still is low productivity per unit area. It is about 2–5 L/m^2 d [1]. So there is an urgent need to enhance the productivity and there are ample opportunities to do so, provided some simple modification are attempted in the conventional type still. The productivity of the solar still is influenced by some atmospheric factors like solar radiation intensity, wind velocity, ambient temperature and humidity of the region. These factors are determined by nature and we have no control over them. The productivity also depends on the solar still basin design, wick material used, thermal storage material used, basin water depth (volume) and basin cover used. Simple modifications in the above operational parameters bring substantial improvement in production.

To increase the basin plate area El-Naggar et al. [2] fabricated a finned basin. Alaian et al. [3] a pin-finned basin. Omara et al. [4] placed a corrugated plate in the basin Velmurugan et al. [5], Abdullah [6] and Alaudeen et al. [7] modified plain basin as stepped basin. Sodha et al. [8], Rajaseenivasan and Murugavel [9], Panchal [10] constructed double basin solar still. Joe Patrick Gnanaraj and Velmurugan [11] designed compartmental single basin and stepped basin solar still to enhance the yield. Essa et al. [12] designed a vertical solar still.

Singh and Francis [13], Verma et al. [14], Gupta and Singh [15] applied Taguchi method to investigate significant parameters and parameter levels. Joe Patrick Gnanaraj and Ramachandran [16] fabricated a robust design solar still by integrating all the best parameter levels identified by the Taguchi method and the distillate output collected was 95.54% higher than the conventional still. Joe Patrick Gnanaraj and Velmurugan [11] applied Taguchi method to fabricate robust design single and stepped basin solar stills.

Different thermal storage materials were used Abdullah [6] used aluminium filling and Raj et al. [17] used stone chips, sand stones and calcium oxide. Srithar et al. [18] spread charcoal and river sand in the basin. Rajaseenivasan et al. [19] applied river sand, metal scrap and charcoal. Panchal [10] used black granite. Murugavel et al. [20] found ¾ inch quartzite rock as the most efficient.

Al-Harahsheh et al. [21] doubled the distillate production by decreasing the basin water level from 10 to 5 cm. Morad et al. [22] found that when basin water increased, distillate production declined. Rajaseenivasan et al. [19] reduced the basin water depth from 8 to 2 cm to increase the distillate yield. Rajaseenivasan and Srithar [23] concluded that lower the basin water depth, higher the efficiency. Park et al. [24] achieved maximum production when the sea water level in basin was 10 mm. Nafey et al. [25] and Kabeel et al. [26] established the inverse relationship between water depth and production. Sampathkumar et al. [27] obtained maximum production when the basin water depth was 0.04 m.

Tanaka [28] and Tanaka and Nakatake [29] used internal and external reflectors to increase the yield. Tanaka [30] used flat plate bottom reflector to focus solar rays into the still. Joe Patrick Gnanaraj et al. [31] focused additional solar radiation with the help of external reflectors. Joe Patrick Gnanaraj et al. [32] used external mirror in double slope solar still.

Malik et al. [33], Duffie and Beckman [34] and Dimri et al. [35] preferred glass still cover over other materials because of its high transmittance. It is also a good condensing cover. Ghoneyem and Ileri [36] preferred 3 mm thick glass cover and Phadatare and Verma [37] 4 mm thick glass cover. Akash et al. [38] concluded that the optimum tilt angle of glass cover was 35°.

Murugavel et al. [20] used jute cloth, coir mate pieces, sponge sheet, light black cotton cloth and waste cotton pieces as wick material. Abu-Hijleh and Rababah [39] spread sponge cubes. Shukla and Sorayan [40] used jute cloth to increase the evaporation. Kabeel [41] used jute cloth in concave basin still. Essa et al. [42] designed a rotating wick solar still.

Expansion of basin plate area increases the absorption of solar radiation. So fins are added in the basin. The plain basin is modified as corrugated basin or stepped basin. To sustain production during the declining and off – sunshine hours, thermal storage materials are spread in the basin. To accelerate and to improve evaporation, wick materials are used. Lower the volume of basin water, higher the productivity. So basin water depth is maintained at the lowest possible level. The basin cover is the medium through which solar rays are transmitted into the basin and it also serves as the plate for condensation of water vapour. So basin cover of suitable material and thickness is selected and used. Additional solar radiation is focused into the still using reflectors. Nowadays preheated water is fed into the still using solar pond, flat plate collector and vacuum tubes.

From the literature study and discussion with various researchers, four operational parameters (factors) that are significant in promoting distillate yield were identified. They are:

- Expansion of basin plate area by fabricating a compartmental basin;
- Maintaining lower basin water depth;
- Placing wicks in the basin;
- Using basin glass cover of appropriate thickness.

Now the task before us is to identify the parameter level in each operational parameter that optimize/maximize production. The number of compartments in the compartmental basin that yield maximum production is to be determined. The basin water depth that optimize production has to be identified. The dimension of the wick has to be decided. In the same way the ideal thick glass basin cover has to be selected. To fulfill the above task, 4 parameter levels in each operational parameter were identified. They are summarized in Table 1.

2. Mathematical modelling

Dunkle [43] proposed the most commonly used relationship to estimate heat and mass transfer coefficient. It is useful in the study of the conventional solar still with most normal range of operation. Adhikari et al. [44] studied the applicability of Dunkle's relationship in solar still with wide range of operating temperature and proposed modifications in it. They proposed new relationship to evaluate heat and mass transfer co-efficient at high temperature ranges.

2.1. Daily production

The production of the still with modification was calculated using the technique used by Joe Patrick Gnanaraj and Velmurugan [45].

Evaporative heat transfer (water to glass):

$$Q_{e,w-g} = h_{e,w-g}\left(T_w - T_g\right) \tag{1}$$

Evaporative heat transfer coefficient (water to glass):

$$h_{e,w-g} = 16.273\times10^{-3}\times h_{c,w-g}\left[\frac{\left(P_w - P_g\right)}{\left(T_w - T_g\right)}\right] \tag{2}$$

Saturated pressure for water:

$$P_w = \exp\left[25.317 - \frac{5,144}{\left(T_w + 273\right)}\right] \tag{3}$$

Saturated pressure for glass:

$$P_g = \exp\left[25.317 - \frac{5,144}{\left(T_g + 273\right)}\right] \tag{4}$$

Convective heat transfer coefficient (water to glass):

$$h_{c,w-g} = 0.884\left[\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)\left(T_w + 273\right)}{268.9\times10^3 - P_w}\right]^{1/3} \tag{5}$$

Determination of per hour production:

$$m_e = \frac{Q_{e,w-g}\times 3,600}{L}\ \text{mL/m}^2\ \text{d} \tag{6}$$

where L is the latent heat of vaporization = 2,372,000 J/kg.

Determination of daily production:

$$\text{Yield}_{\text{per day}} = \sum_{7\text{am}}^{6\text{pm}} m_e \tag{7}$$

Table 2
Metrological and thermophysical parameters

Sl. No.	Type of parameter	Variables considered	Value
1.	Climatic factors	Ambient temperature (°C)	27–45
		Water temperature (°C)	27–67
		Glass temperature (°C)	27–51
		Average wind velocity (m/s)	0.4
		Relative humidity (%)	23–50
		Solar radiation (W/m^2)	0–950
2.	Design	Mass of basin water (m_b)	40–60 kg
		Area of glass surface (A_g)	1 m^2

The efficiency and distillate production of the solar still was calculated by using the values given in Table 2.

3. Experimental setup

The experimental setup had a basin and basin cover. The still basin was fabricated using 2 mm thick iron sheet. The dimension of the basin was – length 100 cm and width 100 cm. At the high end side the height of the basin was 67 cm and at the low end side height was 31 cm. The basin was packed by heat resistant material and placed within a wooden box. The inner side of the basin was painted black to absorb more solar radiation. The still basin was covered by a glass cover and the inclination angle was 20°. To feed water into the still and to collect the distilled water, suitable arrangements were made. The schematic diagram of the solar still is given in Fig. 1, the actual experimental setup in Fig. 2 and heat and mass transfer processes in a solar still in Fig. 3. To facilitate the experiments to be conducted with various modifications, the following arrangements were made.

- Compartmental basin plate – to convert the plain basin into compartmental basin, four basin plates of 40, 60, 80 and 100 compartments were fabricated. The compartmental basin plate was placed inside the still basin and plain basin was modified as compartmental basin. The arrangement of compartments in the compartmental basin is shown in Fig. 4.
- Basin water depth – the compartmental basins have marking for 20, 30, 40 and 50 mm basin water depth and

Table 1
Parameters and parameter levels

Parameter	Levels			
	1	2	3	4
Number of compartments – A	A_1 40	A_2 60	A_3 80	A_4 100
Basin water depth – B	B_1 20 mm	B_2 30 mm	B_3 40 mm	B_4 50 mm
Size of wick (diameter) – C	C_1 10 mm	C_2 20 mm	C_3 30 mm	C_4 40 mm
Basin cover thickness – D	D_1 3 mm	D_2 4 mm	D_3 5 mm	D_4 6 mm

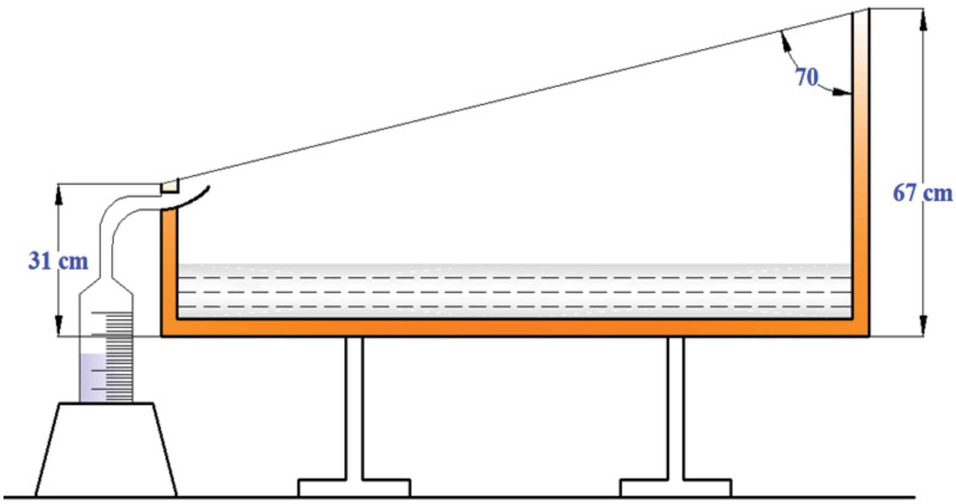


Fig. 1. Schematic diagram of the solar still.

Fig. 2. Experimental setup of solar still.

it is shown in Fig. 5. In the morning the required quantity of water was fed. No top-up of water was done during the course of experiments.

- Wick – wicks were prepared by packing raw cotton inside cylindrical cotton bags. Cylindrical wicks of four different dimensions (diameter) – 10, 20, 30 and 40 mm were prepared and kept ready for the experiments. For each experiment, 50 wicks were used they were placed in the middle of the compartments in a vertical position. The structure of a wick is shown in Fig. 6.
- Glass cover – 3, 4, 5 and 6 mm thick glass basin covers were prepared and kept ready for the experiment. The different glass covers are shown in Fig. 7.

4. Objectives and methodology

Our objective was to identify the combination of parameter levels that optimize/maximize distillation in a solar still using Taguchi method. A robust design solar still was to be fabricated as per Taguchi method and production from this still was to be experimentally determined and compared with estimated production.

Four operational parameters and four levels in each parameter were taken for the study. They are given in Table 1. They were to be combined in all possible ways and the best combination of parameter levels was to be identified. The four parameters and four levels in each parameter will combine in 256 ways. To choose the optimum combination, 256 experiments were to be conducted. To minimize the number of experiments, we resort to Taguchi method. The Taguchi method requires only 16 experiments to be conducted. The parameter levels were combined as per L_{16} orthogonal array and the experiments were conducted. L_{16} orthogonal array and the matrix of experiments are given in Appendix I and II. To minimize the experimental variation, each trial was repeated twice and the average was taken as the response

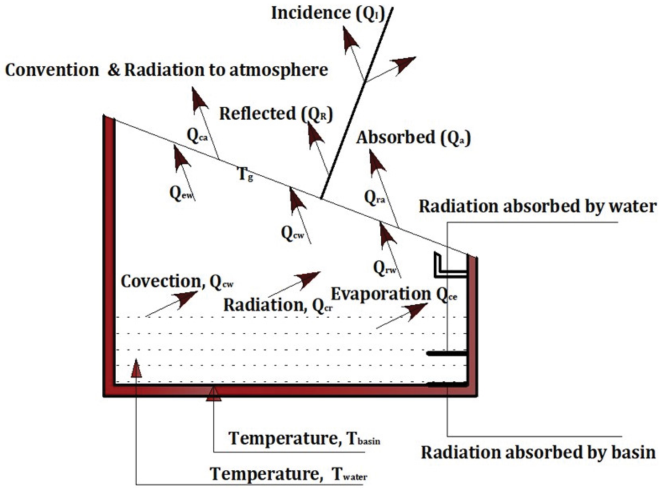


Fig. 3. Heat and mass transfer process.

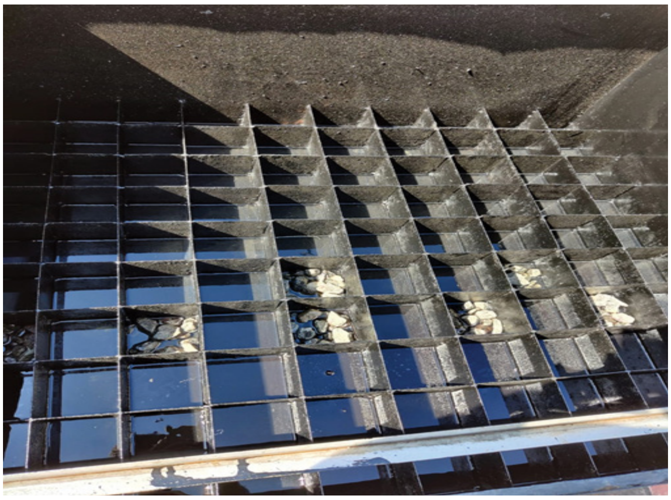


Fig. 4. Compartmental basin plate.

Fig. 5. Basin water depth marking.

Fig. 6. Cylindrical cotton wick.

of the trial. The experimental results were analysed using the following techniques.

- S/N ratio analysis – S/N ratios (signal-to-noise ratio) for all the parameter level were calculated and the parameter level with the highest S/N ratio value was identified as the best parameter level.
- Mean response – mean response value for each parameter level was calculated. The parameter level with the highest mean response value was selected in each parameter.
- Regression analysis – the mathematical relationship between the dependent variable (yield) and independent variables (parameter *A*, *B*, *C* and *D*) was studied using regression analysis
- Analysis of variance – to find out the significant parameters and the contribution of each parameter to production, the analysis of variance (ANOVA) technique was used.
- Estimation of optimum production – the optimum production from robust design solar still was determined using mean response values and regression analysis.

The experiments were conducted in the following steps.

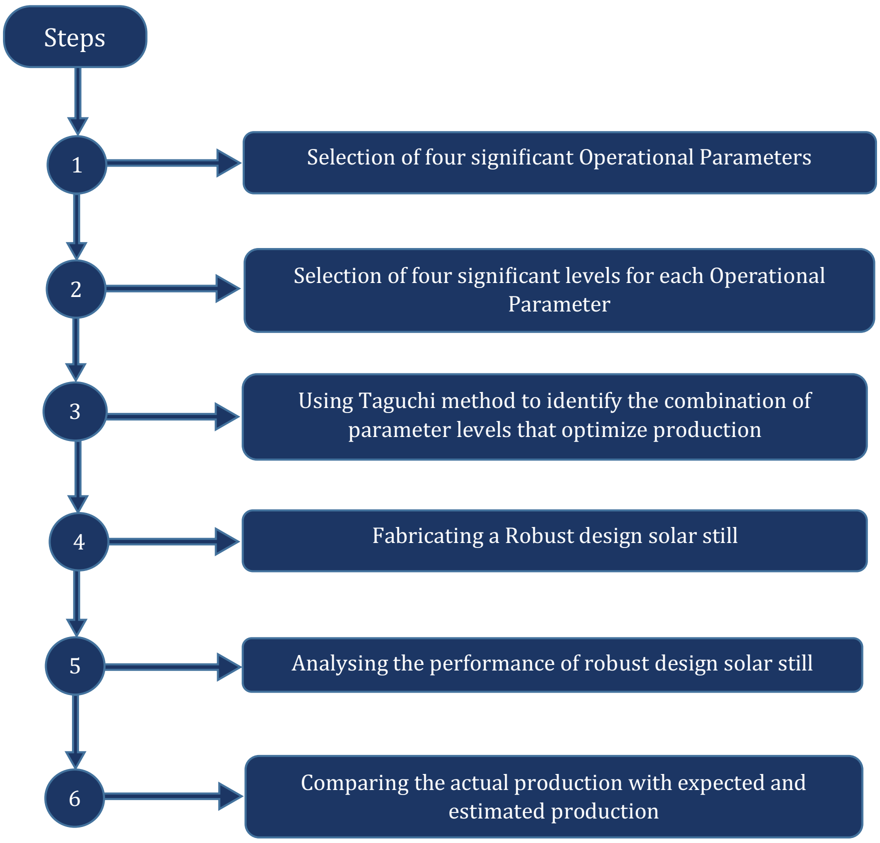


Fig. 7. Basin glass cover.

5. Results and discussion

The experiments were conducted at Caldwell Colony, Tuticorin during the months of March and April 2021. The experiments were started at 7 am and continued up to 6 pm. The distillate collected was recorded at the end of every 1 h and the total production during 11 h (7 am to 6 pm) was recorded as the distillate yield of the experimental setup in a day.

5.1. S/N ratio analysis (signal-to-noise ratio)

The audio concept of signal-to-noise ratio is extended to multi factor experiment. The signal-to-noise ratio (S/N ratio) is a statistic that combines the mean and variance. The objective in robust design is to minimize the sensitivity of a quality characteristic to noise factors. This is achieved by selecting the factor levels corresponding to the maximum S/N ratio (Krishnaiah and Shahabudeen [46]. In larger the better problem, S/N ratio is given by:

$$\text{S/N} = -10\log\left(\frac{1}{n}\sum_{i=0}^{n}\frac{1}{y^2}\right) \quad (8)$$

where Y = value of output; n = number of outputs.

Table 3
Signal-to-noise ratios (larger is better)

Level	*A*	*B*	*C*	*D*
1	68.03	71.91	67.18	68.52
2	68.14	69.92	68.33	69.57
3	68.81	67.88	71.47	69.48
4	71.04	66.32	69.04	68.46
Delta	3.01	5.59	4.29	1.11
Rank	3	1	2	4

A, *B*, *C* & *D* parameters.

S/N ratios for different factor levels are given in Table 3 and shown in Fig. 8. Since our objective is to maximize production, we select those factor levels that has highest S/N ratios.

The S/N ratio values for parameter levels A_4, B_1, C_3 and D_2 are the highest. The parameter levels recommended for maximum production are – 100 compartments in parameter *A*, 20 mm basin water depth in parameter *B*, 30 mm size wick in parameter *C* and 4 mm thick glass basin cover in parameter *D*. So modifying the solar still as compartmental basin with 100 compartments, maintaining 20 mm basin water depth, placing 30 mm size cotton wicks and covering the basin with 4 mm thick glass cover gives maximum production.

The delta value shows the range (difference between the largest and smallest values) in S/N ratios of the parameter levels. On the basis of delta values, the parameters are ranked. For enhancing the productivity of the solar still, the order of modifications attempted must be as per the ranking order. Maintaining recommended basin water depth (20 mm) must be given the top most priority, followed by placing 20 mm size wicks (second priority), replacing the plain basin as compartmental basin with 100 compartments (third priority) and 4 mm thick basin glass cover (fourth priority).

5.2. Mean response

The mean response value of a particular parameter level gives the average performance of that level in different experimental trials. For example, the level C_3 is involved in trials 3, 8, 9 and 14. The average response from the four trials give the mean response value of level C_3. The response values are summarize in the Table 4 and values are shown in Fig. 9.

The parameter level that has the highest mean response value is identified as the best performing parameter level. The parameter levels A_4, B_1, C_3, and D_2 have highest mean response value. So the recommended parameter levels

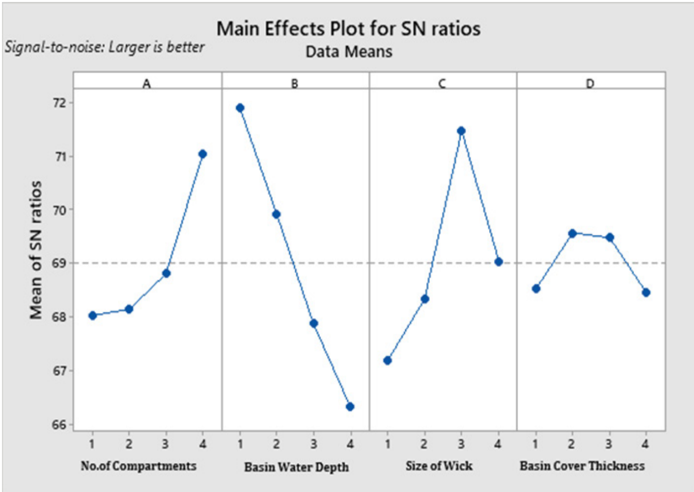


Fig. 8. Parameter levels and S/N ratio values.

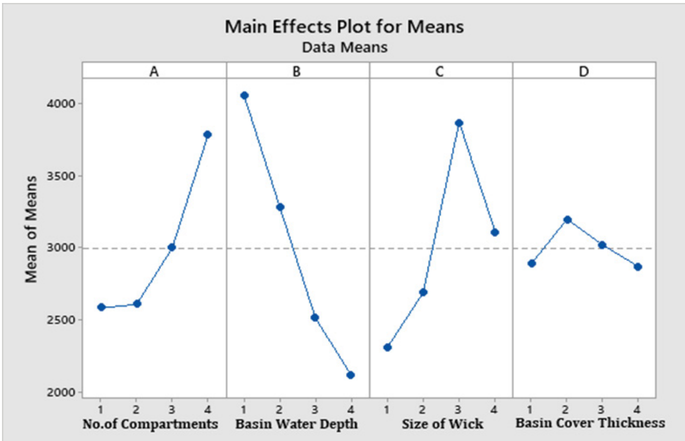


Fig. 9. Parameter levels and mean response values.

Table 4
Mean response values

Level	*A*	*B*	*C*	*D*
1	2,583	4,060	2,305	2,888
2	2,606	3,285	2,689	3,198
3	2,999	2,513	3,871	3,019
4	3,785	2,115	3,108	2,869
Delta	1,203	1,945	1,566	329
Rank	3	1	2	4

A, *B*, *C* & *D* parameters.

are – still basin with 100 compartments, 20 mm basin water depth, 30 mm size wick and 4 mm thick glass basin cover.

The delta value shows the increase in production we can expect when a modification is attempted in a parameter. On the basis of delta values, the parameters are ranked. Since our goal is maximization of production, the order of modification attempted must be in the ranking order. Modification in parameter *B* must be attempted first. After this, modification in parameter *C* may be attempted, followed by modification in parameter *A*. Modification in parameter *D* brings only marginal increase in production. So after attending modification in all other parameters, modification in parameter *D* may be attempted.

5.3. Analysis of variance

To find out the operational parameters that significantly influence the distillate production and the contribution of each parameter to production, the experimental findings were analyzed using ANOVA technique.

5.3.1. Significant parameters

All the operational parameters may not be significant in influencing the production. Some parameters may be only marginal contributors to production. Modification in the significant parameter must be given priority and modification in insignificant parameter may or may not be attempted. The summary of ANOVA findings are given in Table 5. The following hypothesis is formed.

H_0 – operational parameters have no significant influence on production;
$\alpha = 0.05$.

The calculated F-values are greater than the table F-values for parameter A, B, C and D. So we reject the null hypothesis and conclude that parameter A, B, C and D significantly influence the production. We infer that attempting modification in basin design, basin water depth, size of wick and thickness of basin cover can be attempted to improve the productivity of the solar still.

5.3.2. Contribution of parameters

All the parameters may not equally contribute to production. A study on the relative contribution of each operational parameter helps us to identify the parameter or parameters that are to be attended first for significant improvement in production. Modification in the less contributing parameters may be attempted, provided the cost of modification is less. Costly and less contributing parameter may be dropped. The percentage contribution of each parameter is given in Table 5.

Contribution of basin water depth is the highest (48.5%). So maintaining identified basin water depth must be given top most priority. The second priority must be placing wicks of identified size. Its contribution is 29.6%. Designing the still basin as compartmental basin must be our third priority because its contribution is 20.6%. The contribution of ideal thick basin cover is only 1.5%. Modification in the basin cover may be attempted after taking into consideration the cost involved in the modification.

5.4. Regression analysis

In this study, the response (yield) is related to the four operational parameters A, B, C and D. The nature and degree of relationship between the independent variable and dependent variable are explained by regression analysis. It is assumed that the response (Y) is linearly related to four operational parameters and the relationship is written as:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D \quad (9)$$

where Y = response (yield); β_0 = constant; β_1 = regression coefficient of parameter A; β_2 = regression coefficient of parameter B; β_3 = regression coefficient of parameter C; β_4 = regression coefficient of parameter D; A, B, C & D operational parameters.

The regression equation is:

$$Y = 2,806 + 400A - 661B + 359C - 24D \quad (10)$$

Then, we have to test whether linear relationship between dependent and independent variable exists or not. The existence of linear relationship is derived from variance study for multiple regression and it is given in Table 6.

The calculated F-value for regression is greater than the table value. So we infer that there is linear relationship.

After establishing the linear relationship between dependent and independent variables, our next task is to identify the operational parameters that are linearly related to yield. For parameter A, B and C, the calculated F-values are greater than the table value (Table 6). So it is concluded that the parameter A, B and C are linearly related to yield.

The regression coefficients for parameter A, B and C give the nature and quantum of influence the operational parameters can exert on yield. The significance of regression coefficients are tested using t test and it is given in Table 7.

The calculated t values are greater than the table value for the parameter A, B and C and it is concluded that the above three coefficients have significant linear relationship with yield.

The positive regression coefficient of parameter A explains that as the number of compartments in the basin increases the yield also increases. The negative regression coefficient of parameter B reveals that as the basin water depth decreases, the yield increases. In other word, the negative relationship between basin water depth and yield is established. The positive regression coefficient of parameter C shows that as the size of wick increases the yield increases. In sum, large number of compartments, lower basin water depth and large size wicks enhance the yield.

5.5. Robust design solar still

S/N ratio analysis and mean response analysis give the optimum combination of parameter levels and it is given below.

Table 5
Analysis of variance

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
A	3	3,781,531	20.59%	3,781,531	1,260,510	1,063.35	0.000
B	3	8,902,069	48.47%	8,902,069	2,967,356	2,503.22	0.000
C	3	5,401,381	29.41%	5,401,381	1,800,460	1,518.84	0.000
D	3	276,206	1.50%	276,206	92,069	77.67	0.002
Error	3	3,556	0.02%	3,556	1,185		
Total	15	18,364,744	100.00%				

Table 6
Analysis of variance for multiple regression

Source	DF	Seq. SS	Adj. SS	Adj. MS	*F*-Value	*P*-Value
Regression	4	14,520,476	14,520,476	3,630,119	10.39	0.001
A	1	3,200,000	3,200,000	3,200,000	9.16	0.012
B	1	8,731,811	8,731,811	8,731,811	24.99	0.000
C	1	2,577,620	2,577,620	2,577,620	7.38	0.020
D	1	11,045	11,045	11,045	0.03	0.862
Error	11	3,844,268	3,844,268	349,479		
Total	15	18,364,744				

Table 7
Regression coefficient and significance level

Term	Coef.	SE Coef.	95% CI	*T*-Value	*P*-Value
Constant	2,806	677	(1,316; 4,297)	4.14*	0.002
A	400	132	(109; 691)	3.03*	0.012
B	–661	132	(–952; –370)	–5.00*	0.000
C	359	132	(68; 650)	2.72*	0.020
D	–24	132	(–314; 267)	–0.18	0.862

*Significant at 5% level

A_4 – Still basin with 100 compartments;
B_1 – 20 mm water depth;
C_3 – 30 mm size cotton wick;
D_2 – 4 mm thick glass basin cover;

It is assumed that the recommended parameter levels are incorporated in the solar still and robust design solar still is fabricated. The distillate yield of the robust design solar still is estimated using:

- Mean response method;
- Regression technique.

5.5.1. Mean response method

From the mean response value of parameter levels, the distillate yield expected from the robust design solar still is estimated using the formula.

$$\mu = \bar{Y} + \left(\bar{A}_i - \bar{Y}\right) + \left(\bar{B}_i - \bar{Y}\right) + \left(\bar{C}_i - \bar{Y}\right) + \left(\bar{D}_i - \bar{Y}\right) \quad (11)$$

where μ = estimated production; $\bar{Y}$ = overall mean response; $\bar{A}_i, \bar{B}_i, \bar{C}_i$ & $\bar{D}_i$ – mean response of the best parameter level in parameters *A*, *B*, *C* and *D*; *i* is the best level.

The overall mean response $\bar{Y}$ is calculated by adding all the experimental values and dividing the sum by total number of experiments. In this study, 32 experiments were conducted. So $\bar{Y}$ refers to the average yield of 32 experiments.

$$\text{Overall mean response}\left(\bar{Y}\right) = \frac{\text{Total Yield from 32 Experiments}}{32} = 2{,}993.13\ \text{mL/m}^2\ \text{d} \quad (12)$$

The production of the robust design solar still is estimated as:

$$\mu = \bar{Y} + \left(A_4 - \bar{Y}\right) + \left(B_1 - \bar{Y}\right) + \left(C_3 - \bar{Y}\right) + \left(D_2 - \bar{Y}\right)$$

[$\bar{Y}$ = 2,993.13; A_4 = 3,785; B_1 = 4,060; C_3 = 3,871; D_2 = 3,198.
μ = 2,993.13 + (3,785 – 2,993.13) + (4,060 – 2,993.13) + (3,871 – 2,993.13) + (3,198 – 2,993.13) = 5,934 mL/m² d.

5.5.2. Regression method

The production of the robust design solar still can also be estimated by regression technique. The comprehensive regression equation gives the regression coefficient values for all the parameter levels. The comprehensive regressive equation is given below.

$$\begin{aligned} Y = {} & 2{,}993.13 - 410.6A_1 - 386.9A_2 + 5.6A_3 + 791.9A_4 \\ & + 1{,}066.9B_1 + 291.9B_2 - 480.6B_3 - 878.1B_4 - 688.1C_1 \\ & - 304.4C_2 + 878.1C_3 + 114.4C_4 - 105.6D_1 + 204.4D_2 \\ & + 25.6D_3 - 124.4D_4 \end{aligned} \quad (13)$$

From the above regression equation, the constant and regression coefficient of A_4, B_1, C_3 and D_2 levels are taken and listed in Table 8. The significance of the above regression coefficients are tested using *t*-test

The regression coefficients of A_4, B_1, C_3 and D_2 are statistically significant.

The distillate production of the robust design solar still is estimated by the formula.

$$\mu = \beta_0 + \beta_1 A_4 + \beta_2 B_1 + \beta_3 C_3 + \beta_4 D_2 \quad (14)$$

where μ = estimated yield; β_0 = constant; $\beta_1 A_4$ = regression coefficient of level A_4; $\beta_2 B_1$ = regression coefficient of level B_1; $\beta_3 C_3$ = regression coefficient of level C_3; $\beta_4 D_2$ = regression coefficient of level D_2.

$$\mu = 2{,}993.13 + 791.9 + 1{,}066.9 + 878.1 + 204.4 = 5{,}934 \text{ mL/m}^2 \text{ d}$$

5.6. Robust design solar still – experimental production

Robust design solar still was fabricated incorporating all the identified parameter levels. The basin plate was modified as compartmental basin with 100 compartments. In the basin plate, fifty 30 mm size cylindrical cotton wicks were placed in a vertical position. The initial water depth was kept as 20 mm. The still basin was covered by 4 mm thick glass cover. Using the above experimental setup, the experiments were conducted. The distillate production collected from 7 am to 6 pm is recorded as the production from the still in a day. Only the production during a normal day which is free from any abnormal atmospheric condition is considered. The experiments were repeated for 5 d and average was taken as the production of the robust design solar still. The distillate yield collected during 5 d are listed in Table 9. The average production was 5,280 mL/m^2 d.

5.7. Thermal performance of robust design solar still

It is necessary to analyse the thermal performance of robust design solar still. The ambient temperature, water temperature, glass cover temperature and distillate yield were collected at the end of every 1 h and the thermal values collected during one day was taken for a detailed study. The ambient temperature reached the maximum of 45°C at 2 pm. It was above 40°C between 11 am and 4 pm. The basin water temperature reached the maximum of 67°C at 2 pm. From noon to 3 pm, it was above 60°C. The glass cover temperature touched 50°C at 1 pm, continued to remain above this level up to 3 pm and reached the maximum of 51°C. The per hour distillate production stared increasing in the forenoon and reached the maximum of 980 mL at 2 pm. The trend in ambient temperature, basin water temperature, water–glass temperature difference and per hour distillate yield are shown in Fig. 10.

Water temperature, glass cover temperature, water–glass temperature difference and per hour distillate production were maximum at 2 pm. Using the above thermal values the distillate production was theoretically calculated and it was 5,430 mL/m^2 d.

Table 8
Regression coefficient of optimum parameter levels – significance level

Term	Coef.	*T*-Value	*P*-Value
Constant	2,993.13	347.74	0.000
A_4	791.9	53.12	0.000
B_1	1,066.9	71.56	0.000
C_3	878.1	58.90	0.000
D_2	204.4	13.71	0.001

6. Comparison of production

A comparison among estimated production, theoretical production and experimental production is shown in Fig. 11. The actual production was 82% of estimated production and it was 91.5% of theoretical production.

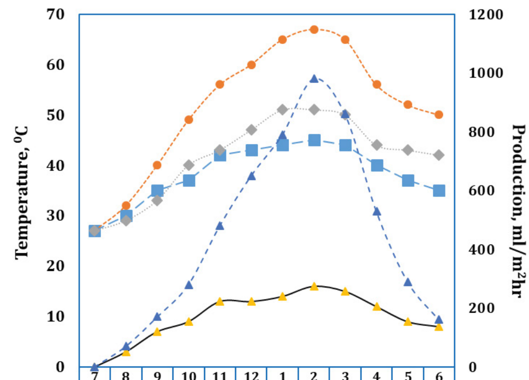
7. Findings

Four operational parameters and four levels in each parameter which were significant in promoting distillate yield were identified and combined as per L_{16} orthogonal array and experiments were conducted. Using Taguchi technique, the four optimum parameter levels were identified. Incorporating the above four parameter levels in solar still basin, a robust design solar still was fabricated and performance were studied. The following inferences were drawn.

- In the four operational parameters taken for study (Number of the compartments in the basin-(*A*), basin water depth-(*B*), size of wick-(*C*) and basin glass cover thickness-(*D*)), the parameter levels of 100 compartments in the basin, 20 mm basin water depth, 30 mm diameter cylindrical wick and 4 mm thick glass cover were identified as best combination for achieving the optimum distillate production.
- Among the four operational parameters considered for enhancing distillate yield of conventional solar still, the top most priority must be assigned for maintaining the optimum water depth. The second priority may be given for identifying and placing ideal size wick, followed by designing a compartmental still basin which is more productive and choosing a basin glass cover of appropriate thickness.
- The number of compartments in the basin has a positive influence on distillate production. As the number of compartments in the basin increases, the distillate production also increases.
- The basin water depth has a negative influence on production. Higher the basin water depth, lower the distillate yield. So it is recommended to lower the basin water depth to the minimum possible level.
- As the dimension of the cylindrical wick (diameter) increases the performance of the solar still increases.
- The most contributing parameter is basin water depth (48.5%). The second and third contributing parameters are size of wicks (20.4%) and number of compartments in the basin (20.6%) respectively.

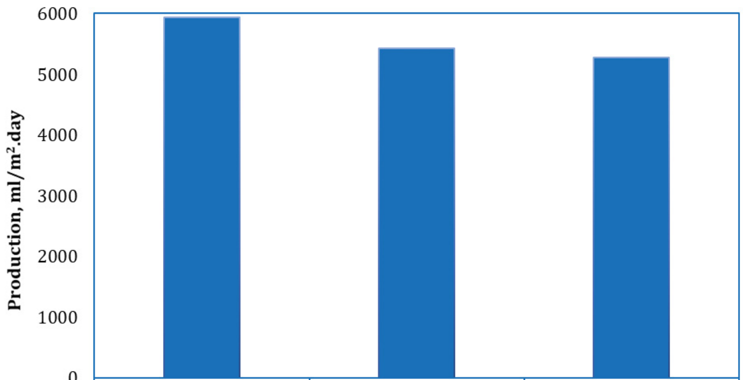
Table 9
Robust design solar still and production

Sl. No.	Date	Production (mL/m^2 d)
1.	5.04.2021	5,240
2.	8.04.2021	5,380
3.	10.04.2021	5,200
4.	13.04.2021	5,320
5.	15.04.2021	5,260
Average		5,280



	7	8	9	10	11	12	1	2	3	4	5	6
Ambient Temperature	27	30	35	37	42	43	44	45	44	40	37	35
Water Temperature	27	32	40	49	56	60	65	67	65	56	52	50
Glass Cover Temperature	27	29	33	40	43	47	51	51	50	44	43	42
W - G Temperature difference	0	3	7	9	13	13	14	16	15	12	9	8
Yield	0	70	170	280	480	650	790	980	860	530	290	160

Fig. 10. Thermal performance of robust design solar still.



	Estimated Production	Theoretical Production	Actual Production
Yield	5934	5430	5280

Fig. 11. Comparison of production.

- The operational parameter, thickness of basin glass cover, is not significant and its contribution is only 1.5%. So, before attempting any modification in still basin cover, we have to take into consideration the cost involved and the benefit expected.
- The estimated optimum production from the robust design solar still was 5,934 mL/m² d.
- The actual production from the robust design solar still was 5,280 mL/m² d and it was 82% of estimated production and 91.5% of theoretical production.

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Appendix

Appendix I
L_{16} (4^4) orthogonal array

Number of compartments	Basin water depth	Size of wick (Dimension)	Basin cover thickness	Production, mL/m² d	
				Response 1	Response 2
40	20	10	3	2,750	2,910
40	30	20	4	2,820	2,740
40	40	30	5	2,940	3,090
40	50	40	6	1,710	1,700
60	20	20	5	3,420	3,390
60	30	10	6	2,080	2,110
60	40	40	3	2,130	2,150
60	50	30	4	2,750	2,820
80	20	30	6	4,860	4,790
80	30	40	5	3,420	3,390
80	40	10	4	2,060	2,030
80	50	20	3	1,710	1,730
100	20	40	4	5,130	5,230
100	30	30	3	4,890	4,830
100	40	20	6	2,810	2,890
100	50	10	5	2,240	2,260

Appendix II
Matrix of experiment

Runs	Factors			
	A	*B*	*C*	*D*
1.	1	1	1	1
2.	1	2	2	2
3.	1	3	3	3
4.	1	4	4	4
5.	2	1	2	3
6.	2	2	1	4
7.	2	3	4	1
8.	2	4	3	2
9.	3	1	3	4
10.	3	2	4	3
11.	3	3	1	2
12.	3	4	2	1
13.	4	1	4	2
14.	4	2	3	1
15.	4	3	2	4
16.	4	4	1	3