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Application of Taguchi method to determine the optimal water depth and glass cooling rate in solar stills

A.H. Elsheikh[a], S.W. Sharshir[b], A.E. Kabeel[c,*], and R. Sathyamurthy[c,d]

a. *Department of Production Engineering and Mechanical Design, Faculty of Engineering, Tanta University, Tanta, Egypt.*
b. *Department of Mechanical Engineering, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt.*
c. *Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt.*
d. *Department of Automobile Engineering, Hindustan Institute of Technology and Science, Chennai-603103, Tamil Nadu, India.*

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Abstract. The current study investigates the optimization of productivity of Solar Stills (SSs) at different levels of solar radiation intensity, film cooling flow rates, and water depths. In this regard, Taguchi method was applied to perform few experiments and find the optimal water depth and cooling rate that could maximize the productivity. An L_9 orthogonal array, signal-to-noise ratio, and Analysis of Variance (ANOVA) were used to investigate the influence of the operating parameters on the SS productivity. The results from Taguchi method and ANOVA revealed that water depth was the most influencing parameter. According to the results, while increasing the solar radiation and water film cooling would improve the productivity, increasing the flow rate more than 4 kg/hr had a negligible effect on the productivity. However, decreasing water depth would significantly enhance productivity due to faster rates of evaporation and condensation. This improvement in productivity by film cooling was about 6.05% at the optimal water depth of 0.5 cm while the cold-water flowed over the glass at 2 kg/hr. A regression equation was formulated to determine the relation between the operating parameters as independent variables and the productivity as a dependent variable.

1. Introduction

Water covers approximately 70% of the Earth's surface; however, only about 1% of this water is fresh and the rest includes brackish and saline, making it inappropriate for daily consumption. Today, lack of drinkable water supply is one of the critical problems in a number of countries, thanks, partly, to rapid growth of human population and industrial development. Exploiting solar energy to solve the problem of energy and water scarcity has caught the attention of many researchers [1–7].

Solar stills (SSs) are one of the cheapest and easiest techniques used for water desalination to provide freshwater. A number of researchers have studied designs of different SSs [8–13] and investigated different parameters such as efficiency and productivity affecting their performance [14–18]. To achieve high efficiency, the difference between the temperatures of both basin water temperature and glass cover must be maximized or, precisely speaking, it must be optimized and con-

*. *Corresponding author.*
E-mail addresses: ammar_elsheikh@f-eng.tanta.eg (A.H. Elsheikh); swellamali@yahoo.com (S.W. Sharshir); kabeel6@f-eng.tanta.edu.eg (A.E. Kabeel); raviannauniv23@gmail.com (R. Sathyamurthy)

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trolled [19]. To this end, several modifications have been proposed, namely using external fan for forced convection cooling [20], an external condenser [21], a dye [22], organic colloids [23], nano-composite phase change materials [24], hybrid basin materials [25], distillate condensation on the back of a flat-plate solar collector [26], and film cooling over the glass cover [27,28].

Water film flow over glass cover can significantly minimize glass temperature; hence, the temperature difference between the glass cover and the water surface increases, which in turn increases the circulation rate inside the still and the rate of water condensation on the inner surface of the glass cover [19]. Radiation and convection energy losses from the SS to the surrounding area are minimized. Furthermore, it keeps the self-cleaning process of the glass cover nonstop, leading to enhancement of the SS efficiency.

Another operating parameter that affects the performance of SSs is water depth. Many researchers have studied the influence of changing the water depth inside the still on the SS productivity. Tripathi and Tiwari [29] investigated the effect of different water depths (0.05 m, 0.1 m, and 0.15 m) on the SS productivity and found that maximum productivity was obtained at 0.1 m. A decrease in the productivity at great water depths may occur because the water bulk requires a longer amount of time to warm up.

In the present study, the effects of operating parameters, including water depth and film cooling flow rate, and metrological parameters, such as solar intensity, on the SS productivity were investigated. While water depth and film cooling flow rate are considered as controllable parameters, solar intensity is out of control and is affected by the time of day, season, and location, i.e., latitude and longitude, of conducting the experiments. Another significant uncontrollable metrological parameter is the wind speed that randomly varies in the daytime. Fortunately, the effect of wind speed on the SS performance can be ignored in the case of using film cooling and well-insulated SS [30]. However, as it still exists, it is considered to be a noisy factor in this study.

To determine the effects of optimal operating and metrological parameters on the SS performance, first, it is required to identify those parameters with maximum effect on the SS productivity using a proper statistical method. Traditional optimization methods that comprise a variation of one parameter while holding other parameters at certain constant values are often considered as expensive and exhaustive options. However, designing experimental methods [31,32] can provide easier and efficient approaches to optimizing several operational parameters. Taguchi approach [33–38], as a well-known design of experimental method, is usually used to design the experiments and analyze the obtained results. Taguchi approach provides better reproducibility and consistency than other traditional techniques [39]. Furthermore, through this method, numerous parameters can be investigated and optimized simultaneously to obtain more quantitative information from fewer experimental runs. Before conducting the experiments, two main objectives must be fulfilled, i.e., determining the number of experimental runs and specifying the conditions for each run [40]. After predicting the values of the optimal parameters, confirmation experiments should be conducted [41]. These confirmation experiments are of significance in verifying the accuracy of the applied methodology.

The objective of the current study was to better understand the effects of the operating parameters of the SS, i.e., solar radiation, film cooling flow rate, and water depth, on the freshwater productivity by conducting experiments and analyzing the results through designing an experimental approach (Taguchi analysis). To this end, Taguchi analysis method was employed to determine the statistical significance of the effects of the independent variables (solar radiation, film cooling flow rate, and water depth) on the parameter under study (fresh water productivity). The experiments were conducted at different solar radiation intensities (5587, 5673, and 5741 $W/m^2/day$), film cooling flow rates (2, 4, and 6 kg/hr), and water depths (0.5, 1, and 1.5 cm). Based on the Taguchi analysis results related to the statistical significance of different parameters, several equations for the fresh water productivity were developed.

In the rest of this paper, the following issues are discussed:

- The experimental setup used in this study is described in detail;
- Uncertainty analysis is carried out and the specifications of the used measurement instruments are presented;
- Experimental design based on L_9 orthogonal array is presented;
- Statistical methods including Taguchi and ANOVA analyses are used to analyze the results;
- A regression equation is formulated to correlate the relationship of the operating parameters with the productivity.

2. Experimental setup

Experiments were carried out in summer during August and September on two similar fabricated SSs at Energy and Power Engineering School, Huazhong University of Science and Technology, Wuhan, China (Latitude of 29°58°N and longitude of 113°53°E). The schematic of the SSs setup is shown in Figure 1. Two identical SSs

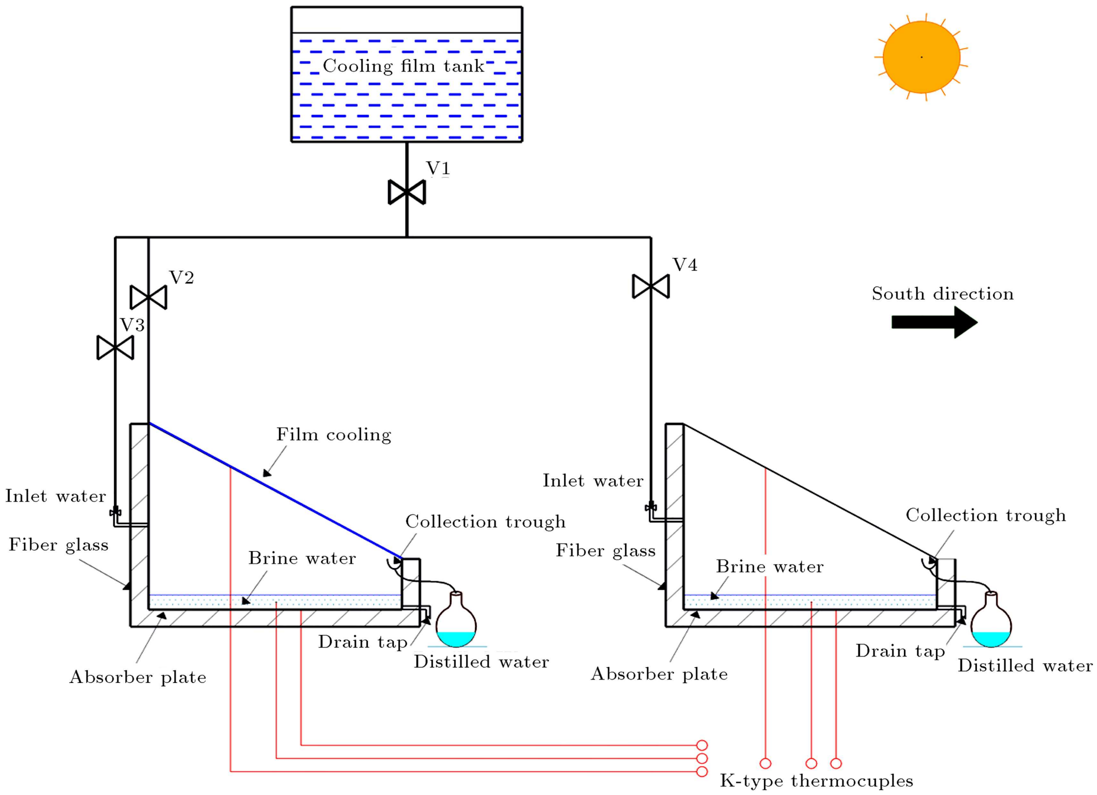

Figure 1. Experimental setup schematic diagram.

with glass film cooling come from a cold-water tank through pipes controlled by control valves (V_1, V_2, V_3, and V_4). The dimensions of the cold-water tank are 88 × 42 × 42 cm. SSs contain basin areas equal to 0.25 m^2 (0.5 m long and 0.5 m wide). The heights of the low and high sides of the SSs are 160 mm and 450 mm, respectively. The SSs are made of iron sheets with thickness of 1.50 mm. To achieve better solar radiation absorbance inside the still in order to increase the evaporation rate, all inner surfaces of the still are coated using black paints. To eliminate heat losses as much as possible and reduce the related errors of such energy losses during the experiments, all side and bottom surfaces are well insulated by fiberglass with the thickness of 5 cm. A trough is attached beneath the glass cover inside the still to collect the distillate water into an external calibrated flask through pipes. The drained brine water is wasted outside the still through another pipe. The upper surface of the still is covered with a clear glass sheet with thickness of 3.5 mm and an inclination angle from the horizontal equal to the latitude of Wuhan, China (approximately 30°), facing the south to maximize the received insolation as much as possible.

The increasing water vapor from basin condenses on the inner surface of the glass covers due to gravity and glass tilting. The condensed water runs down through an inclined channel (trough) into the flask. During the experiments, the total solar intensity, air velocity, glass and brine water temperatures, ambient temperature, and amount of distillated water are measured. Experiments are conducted at the School of Energy and Power engineering, Huazhong University of Science and Technology, Wuhan, China during August and September from 8 am to 5 pm.

3. Uncertainty analysis

During the experiments, the total solar intensity, air velocity, glass and brine water temperatures, ambient temperature, and amount of distillated water are measured. Measuring instruments' specifications depending on the used commercial types in this study as well as their accuracies and ranges are presented in Table 1. The uncertainties of the obtained experimental results are calculated according to the model proposed in [42]. The uncertainty limits of the temperature measurement were about 0.05°C, calculated according to the following equation in terms of the freezing and boiling temperatures for water being 0°C and 100°C [43]:

$$S_T=\left[\left(\frac{\partial T_a}{\partial T_{b,m}}S_{T_{b,m}}\right)^2+\left(\frac{\partial T_a}{\partial T_{f,m}}S_{T_{f,m}}\right)^2+\left(\frac{\partial T_a}{\partial T_m}S_{T_m}\right)^2\right]^{1/2}, \quad (1)$$

where T_a, $T_{b,m}$, $T_{f,m}$, and T_m are the actual, measured boiling, measured freezing, and measured temperatures, respectively. Moreover, $S_{T_{b,m}}$, $S_{T_{f,m}}$, and S_{T_m} are the uncertainties in $T_{b,m}$, $T_{f,m}$, and T_m, respectively, and they have the same values for all thermocouples used in experiments.

4. Experimental design

Experiments were carried out in Wuhan, China during August and September from 8 am to 5 pm. Instead of conducting experiments with possible combinations of all parameter levels like the full factorial design, Taguchi method was applied to perform only few pairs of combinations. Taguchi method is considered the best experimental design method when there are intermediate number of parameters with few interactions [44]. It has a special design of orthogonal arrays used for investigating all parameters with a small number of experiments. According to the Taguchi methodology of parameter design, an experimental design paradigm must be selected for the parameters under study. In this study, an L_9 orthogonal array (three parameters with three levels for each parameter in nine runs of experiments) was implemented. Orthogonal array comprises nine rows representing the number of the runs, i.e., a specific set of parameter levels to be examined. The studied parameters as well as their codes and levels (values) for the implementation in the current Taguchi study are given in Table 2.

In this implementation, while the control factors (incident solar radiation, film cooling flow rate, and water depth) are the independent parameters, productivity is the dependent parameter. The standard design for L_9 orthogonal array with three parameters at three levels is shown in Table 3 where there are nine experimental runs to be carried out with different combinations between the various parameters and their levels. There are many uncontrollable factors that may affect the performance of the SS such as wind speed

Table 1. Measuring instruments' specifications.

Measured parameter	Instrument	Range	Accuracy	Error (%)
Temperature	Calibrated copper constantan-type thermocouples connected to a digital temperature indicator (model TES-1310)	–50 to 280°C	±1°C	0.5
Solar intensity	Solar meter (model TES-1333)	0–2000 W/m^2	±10 W/m^2	0.25
Air velocity	Vane-type digital anemometer (model Benetech GM816)	0–30 m/s	±1 m/s	5
Productivity	A graduated cylinder	1.5 l	±0.002 l	10

Table 2. Codes and level values of parameters.

Parameter	Code	Level 1	Level 2	Level 3
Incident solar radiation (W/m^2/day)	A	5741	5673	5587
Film cooling flow rate (kg/hr)	B	2	4	6
Water depth (cm)	C	0.5	1	1.5

Table 3. Taguchi L_9 orthogonal array.

	Operating parameters		
Run	**Incident solar radiation (W/m^2/day)**	**Film cooling flow rate (kg/hr)**	**Water depth (cm)**
1	A1	B1	C1
2	A1	B2	C2
3	A1	B3	C3
4	A2	B1	C2
5	A2	B2	C3
6	A2	B3	C1
7	A3	B1	C3
8	A3	B2	C1
9	A3	B3	C2

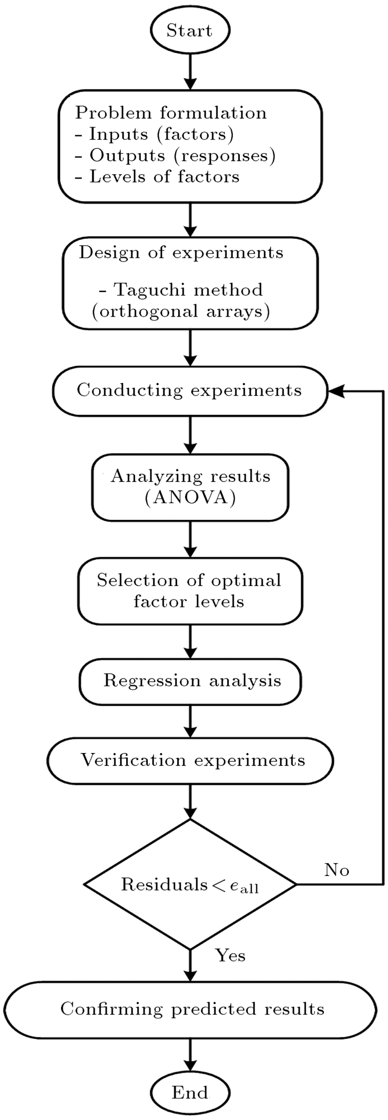

Figure 2. Flow diagram of the proposed approach.

and humidity. These factors are regarded as noise sources. To identify the effects of these noise sources on the performance, each experiment was conducted two times using two similar SSs, which operated simultaneously. The implementation of the proposed design of experiment methodology can be illustrated using a flow diagram, shown in Figure 2.

5. Results and discussion

5.1. Calculations and statistical analysis

In order to analyze the results of the experiments, the mean productivity or the mean response (m_r) for each day, i.e., for each run and the signal-to-noise ratio (SN_L), were utilized. In this respect, the larger-the-better characteristic for obtaining the maximum productivity was taken into account to assess the SS performance based on SN_L ratio. Then, m_r and SN_L were calculated using the following equations:

$$m_r = \frac{\sum_{i=1}^{n} r_i}{n}, \tag{2}$$

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{r_i}^2}\right), \tag{3}$$

where m_r is the mean response, SN_L is the signal-to-noise ratio calculated based on the larger-the-better criterion, n is the total number of runs, and r_i is the response (productivity) at run number i.

In addition, a quantitative investigation using variance analysis was conducted to assess the effectiveness of these parameters and determine the confidence level for each parameter to achieve maximum productivity. A statistical analysis was also performed using ANOVA technique to figure out the statistical significance of each parameter. The F-test was implemented to find the most effective parameter for the SS productivity with the highest ratio between two variances. Variances measure how far the data are dispersed from the mean. The larger the ratio, the greater the effect of the parameter on the SS productivity. The experimental results, i.e., SSs productivity, as well as those from variance analysis for the nine runs are given in Table 4.

The effect of each parameter on the productivity and SNL ratio is shown in Figure 3(a) and (b), respectively. As shown in these figures, both SS productivity and SNL increase upon increasing the solar radiation intensity and film cooling flow rate; however, a rapid decrease in both responses would result from increasing water depth.

Table 5 shows the results of the statistical analysis of the conducted experiments, i.e., degree of freedom, F-value, P-value, adjusted mean squares, and adjusted sums of squares [45]; all were calculated using the following formulas:

$$ASS = \sum_{i=1}^{n} (r_i - \bar{r})^2, \tag{4}$$

$$AMS = \sum_{i=1}^{n} \frac{(r_i - \bar{r})^2}{DF}, \tag{5}$$

$$F = \frac{AMS}{AMS_e}, \tag{6}$$

where ASS is the sum of squares, AMS is the mean squares, DF is the degree of freedom, r_i is the response (productivity) at run number i, $\bar{r}$ is the mean response, and the subscript e is the error.

The given values in Table 5 indicate that water depth has a significant effect on the SS productivity since it has maximum F-value and minimum P-value.

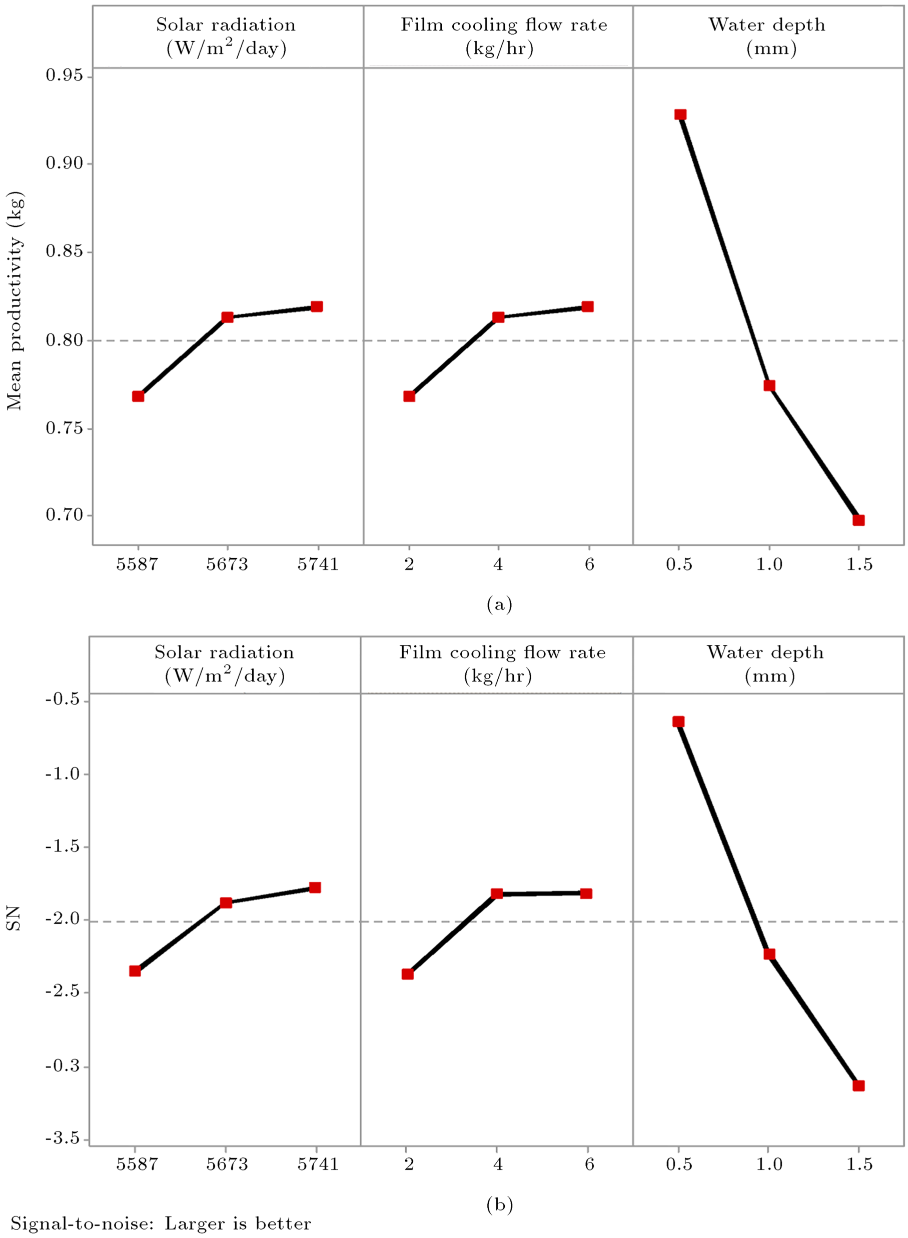

Figure 3. Effect of each parameter means on (a) the productivity and (b) the SN_L ratio.

Table 4. Results of experiments, mean productivity, and SN_L.

Run	Operating parameters			
	Productivity of SS no. 1 (kg)	**Productivity of SS no. 2 (kg)**	**Mean productivity (kg)**	SN_L
1	0.915	0.920	0.9175	–0.74798
2	0.825	0.830	0.8275	–1.64476
3	0.710	0.715	0.7125	–2.94446
4	0.730	0.735	0.7325	–2.70400
5	0.720	0.730	0.7250	–2.79386
6	0.985	0.980	0.9825	–0.15343
7	0.660	0.650	0.6550	–3.67593
8	0.890	0.885	0.8875	–1.03674
9	0.765	0.760	0.7625	–2.35534

Table 5. Parameters of the analysis of variance for means.

Source	Degree of freedom	Adjusted Mean Squares (AMS)	Adjusted Sums of Squares (ASS)	F-value	P-value
Solar radiation	2	0.004643	0.002322	1.58	0.387
Film cooling flow rate	2	0.004643	0.002322	1.58	0.387
Water depth	2	0.083572	0.041786	28.48	0.034
Error	2	0.002935	0.001467		
Total	8	0.095793			

Table 6. Mean productivity and SN_L values for all parameters at all levels.

Parameter	Level	Mean productivity (kg)	Mean SN_L	$\Delta_{prod.}$	Δ_{SN_L}
Incident solar radiation (W/m^2/day)	5741	0.7683	–2.3560	0.0508	0.5769
	5673	0.8133	–1.8838		
	5587	0.8192	–1.7791		
Film cooling flow rate (kg/hr)	2	0.7683	–2.3760	0.0508	0.5582
	4	0.8133	–1.8251		
	6	0.8192	–1.8177		
Water depth (cm)	0.50	0.9292	–0.6460	0.2317	2.4920
	1.00	0.7742	–2.2347		
	1.50	0.6975	–3.1381		

In addition, both solar radiation intensity and film cooling flow rate equally affect the productivity. However, their effects are more negligible than that of water depth. The same conclusion can be drawn from Table 6 suggesting that water depth has the highest SN_L value, implying that it has the greatest effect on productivity among all other parameters. Furthermore, the solar radiation intensity and film cooling flow rate contribute equally to productivity since they have approximately the same mean productivity and SN_L.

According to what has been discussed, in order to maximize the SS productivity, the following values for operating parameters are selected: incident solar radiation of 5673 W/m^2/day, film cooling flow rate of 6 kg/hr, and water depth of 0.5 cm (see Tables 4 and 5). This combination of the values for parameters has the largest SN_L among all other available combinations and, hence, maximal productivity. In addition, increasing the film cooling flow rate up to more than 4 kg/hr has slight influence on the productivity (see Table 6). Moreover, decreasing the water depth to less than 0.5 cm may form small dry spots which decrease the water surface area and, thus, decreasing the SS productivity.

Regression analysis was employed in this study to model the mathematical behavior of the SS productivity. The developed regression equation describing the relationship between productivity and solar radiation as well as film cooling flow rate and water depth is given below:

$$P = -0.94 + 0.000338S + 0.0452R - 0.2317D, \quad (7)$$

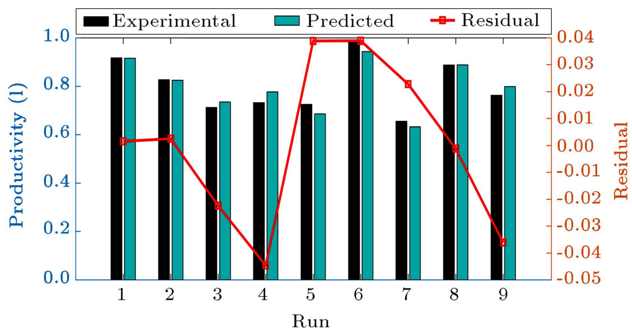

Figure 4. Regression model results: predicted response, actual response, and residuals.

where P is the productivity, S is the solar radiation (W/m^2/day), R is the film cooling flow rate (kg/hr), and D is the water depth (cm).

This regression equation can be used to predict the values for SS productivity at solar radiation (from a historical data available at certain location), certain water depth, and film cooling flow rate. It is worth noting that metrological parameters such as solar radiation can be determined by applying a simple method adopted from the ASHRAE algorithm, widely used by the engineering community. Figure 4 shows a graphical comparison between the predicted results from the regression model and the actual experimental results as well as the residuals of the predicted and the actual response. The agreement between the predicted and actual results reveals the ability of the developed model to predict the productivity of SSs.

This could contribute to determining the optimal operating parameters prior to field operation, which would consequently increase SS efficiency. Furthermore, upon determining the regression model and assessing the influence of the operating parameters on the productivity based on statistical analysis, validation experiments are carried out to examine the reliability of the model. The comparison of the results from the model with the experimental results shows significant consistency, confirming that the proposed experimental design is accurate, effective, and robust. Figure 5 shows the predicted values of productivity for various operating parameters given in Table 7. A significant increase in productivity is observed upon decreasing the water depth. In addition, a moderate increase is observed in productivity upon increasing the film cooling flow rate and the solar radiation intensity. According to Figure 5(a) and (c), the productivity of SS remarkably increases while decreasing the water depth (from 4 to 0.2 cm). Furthermore, productivity would increase by 1.242 l when the solar radiation intensity is kept constant and the film cooling flow rate changes from 0 to 8 kg/h, and by 0.982 l, when the film cooling flow rate is kept constant and the solar radiation intensity changes from 5500 to 5800 W/m^2/day. However, it is increased by only 0.463 l when the water depth is kept constant and the solar radiation intensity and film cooling flow rate are increased by the same aforementioned values, as shown in Figure 5(b), indicating the significant effect of the water depth on the SS's productivity compared with the solar radiation intensity and film cooling flow rate.

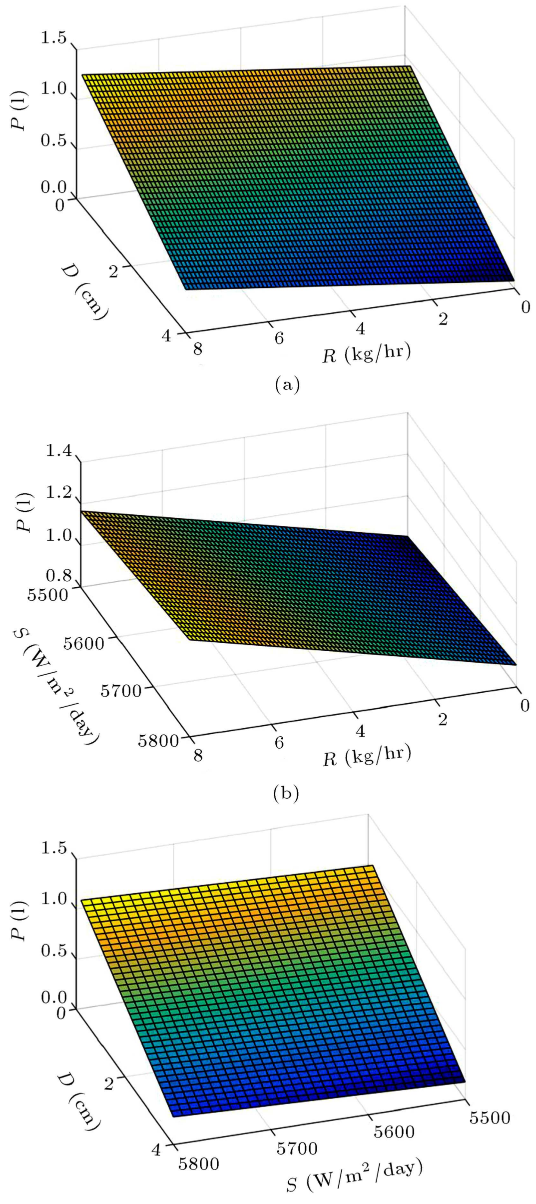

Figure 5. Regression results: (a) Effect of film cooling (R) and water depth (D) on productivity (P), (b) effect of solar radiation intensity (S) and film cooling on productivity, and (c) Effect of water depth and solar radiation intensity on productivity.

5.2. Performance of still with and without cooling

The results and discussions for the measured data of the proposed stills with and without film cooling are presented in this section. Figure 6 show hourly variation in solar intensity, glass and water, and cooled water temperatures of the SS with and without film cooling. The temperatures of water, glass, and film cooling increased upon increasing solar intensity and reached their peak values at noon and then, decreased at sunset, as illustrated in Figure 6. Of note, the temperature difference between water and glass in the case of cooling glass reached 36°C while it was 29°C without cooling at 0.5 cm brine depth, as shown in Figure 6.

Figures 7 and 8 present a comparison between hourly and accumulated productivity rates of the stills with and without cover cooling. The output distillate increases since morning with the solar radiation reaching its peak value at noon and it decreases with the solar intensity reaching its minimum value at sunset for both SSs with and without cooling. Moreover, the hourly yield is larger for SS with cooling by about 6.05% at a brine depth of 0.5 cm in the basin and a cold-water flow rate of 2 kg/hr over the glass, compared with that of the SS without cooling and the same water depth. Due to slight increases (6.05%) in the productivity of the still using water film cooling over the conventional still, it is highly desirable to investigate the integration of the film cooling technique with other productivity augmentation techniques, such as application of nanofluids, phase change materials, and thermal storage materials, to obtain greater productivity.

Table 7. Parameters ranges used in regression results shown in Figure 7.

Parameter	Figure 4(a)	Figure 4(b)	Figure 4(c)
Incident solar radiation (W/m^2/day)	5741	5500–5800	5500–5800
Film cooling flow rate (kg/hr)	0–8	0–8	4
Water depth (cm)	0.2–4	0.5	0.2–4
Increase in the productivity (l)	1.242	0.463	0.982

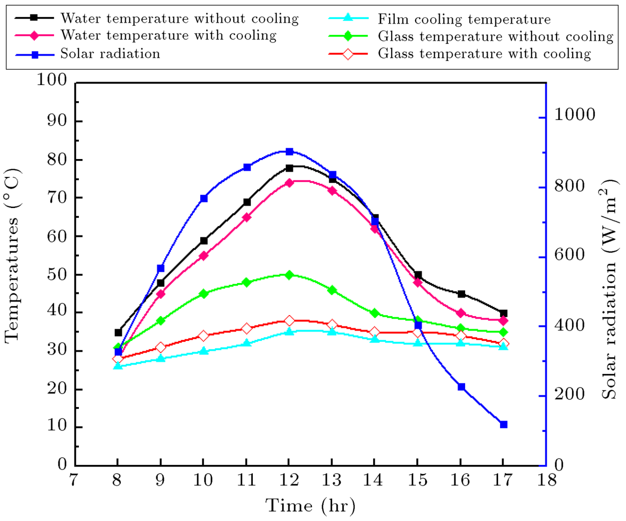

Figure 6. Hourly solar intensity, glass, water and film cooling temperatures with and without cooling.

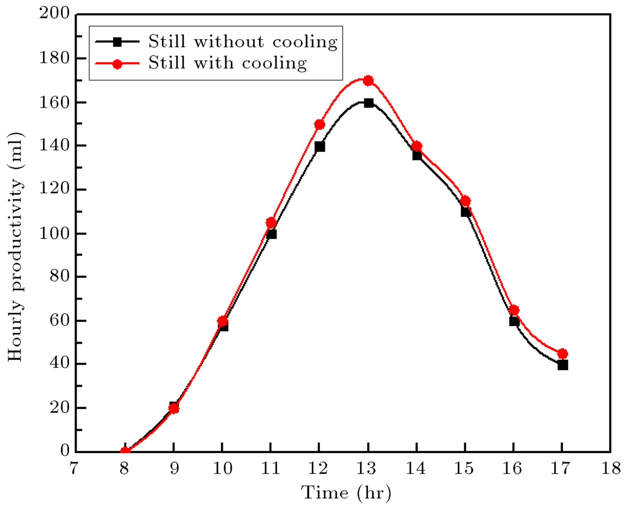

Figure 7. Hourly productivity for the stills with and without cooling.

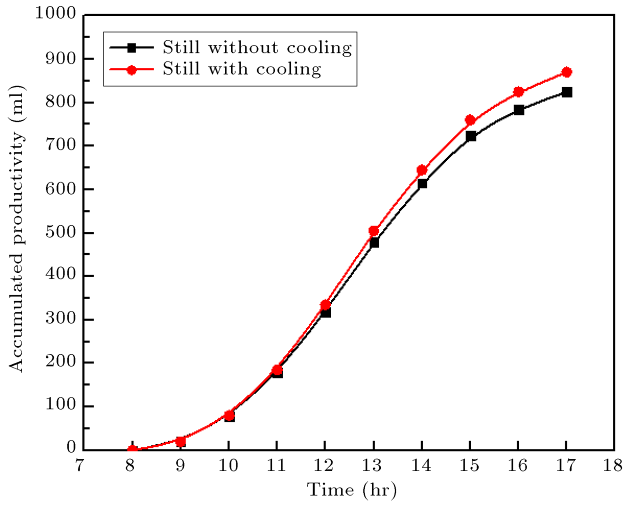

Figure 8. Accumulated productivity for the stills with and without cooling.

6. Conclusion

In this study, the Taguchi method and analysis of variance were employed to select the optimal operating conditions for solar stills. A basic L_9 orthogonal array with 9 experimental runs was applied to three operating parameters (solar radiation intensity, water film cooling, and water depth), each at three levels, to determine the most effective one in terms of productivity. The investigation confirmed that water depth had the greatest influence on the productivity. To obtain maximum productivity, the values for the following operating parameters were selected: incident solar radiation, 5673 W/m^2/day; film cooling flow rate, 6 kg/hr, and Water depth, 0.5 cm. However, decreasing the water depth to less than 0.5 cm would result in forming small dry spots, which could decrease the water surface area, thus decreasing the solar still productivity. Furthermore, increasing the film cooling flow rate up to more than 4 kg/hr had a slight effect on the productivity. Regression model was developed to determine the relationship between the operating parameters and productivity. Confirmation experiments showed good agreement between the experimental and predicted values.

Nomenclature

AMS	Adjusted Mean Squares
ANOVA	Analysis of Variance
ASS	Adjusted Sum of Squares
D	Water depth
DF	Degree of Freedom
P	Productivity

R	Film cooling flow rate
S	Solar radiation
SN_L	Signal to Noise Ratio
SS	Solar Still
A	Code of incident solar radiation
B	Code of film cooling flow rate
C	Code of water depth
e	Error
e_{all}	Maximum allowable error between the predicted and actual data
m_r	Mean response
n	Total number of runs
r	Response (productivity)
S_T	Uncertainty limit of the temperature measurement
$\Delta_{prod.}$	Change in productivity
Δ_{SN_L}	Change in signal to noise ratio
$S_{T_{b,m}}$	Uncertainty of the measured boiling temperature
$S_{T_{f,m}}$	Uncertainty of the measured freezing temperature
S_{T_m}	Uncertainty of the measured temperature
T_a	Actual temperature
$T_{b,m}$	Measured boiling temperature
$T_{f,m}$	Measured freezing temperature
T_m	Measured temperature

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Biographies

Ammar H. Elsheikh was born in 1985 in Elmahalla Alkubra, Egypt. He received his BSc and MSc degrees in Mechanical Engineering from Tanta university, Tanta, Egypt and PhD degree from Huazhong University of Science and Technology, Wuhan, China. He is currently working as an Assistant Professor in Production Engineering and Mechanical Design Department, Tanta university, Egypt. His research interests include renewable energy, manufacturing systems, and applications of ANN techniques for engineering problems. He has published more than 20 articles and has been awarded the Academic Excellence Award of Huazhong University of Science and Technology for Outstanding International Students in 2018.

Swellam W. Sharshir was born in Kafrelsheikh, Egypt. He received his BSc degree in Mechanical Engineering from the Kafrelsheikh University, Egypt in 2008 and MSc degree in Mechanical Power Engineering from the Tanta University, Egypt in 2013. He received his PhD degree in Thermal Power Engineering, School of Energy and Power Engineering, Huazhong University of Science and Technology (HUST), China in 2017. He is an Assistant Professor at the Department of Mechanical Engineering, Kafrelsheikh University. Currently, he is a Postdoctoral Fellow at HUST, China. His research interests are solar desalination solar energy applications, nanofluid, and applications, and management of energy resources, and renewable energy. He has been awarded the Academic Excellence Award of HUST Outstanding International Students in 2017.

Abdelnaby Kabeel received his PhD degree in Mechanical Power Engineering from University of Technology, Bratislava, Slovak Republic in 1997. He is the Vice Dean for Postgraduate Studies and Research, Faculty of Engineering, Tanta University, Tanta. He was the Head of Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt (2013-2016). He was the director of the Center for Science and Environmental Technology at the University of Tanta 2015. He was also the Vice Chairman of Research and Consultation Center Management Engineering, Faculty of Engineering, Tanta University from 2011 to 2013. He was the Vice Chairman of the Board and Management Unit production workshops, Faculty of Engineering, Tanta University from 2011 to 2013.

Ravishankar Sathyamurthy was born in 1988 in Tamil Nadu and received his BSc in Mechanical Engineering and pursued his post-graduate degree in Thermal Engineering at Anna University of Technology, Thirunelveli in 2012 and received his PhD degree Mechanical Engineering from Hindustan Institute of Technology and Science, Chennai in 2016. He has published papers in 90 reputed international journals, 2 patents, and 8 international conferences. His research interests include solar desalination, renewable energy technologies, thermal energy storage, nano-materials, bio-diesel, and combustion modeling. He has reviewed more than 300 research articles from journals such as Renewable and Sustainable Energy-A Review, Journal of Applied Fluid Mechanics, International Journal of Renewable Energy Research, Institute of Engineers (India): Series C Case Studies in Thermal Engineering, Journal of Solar Energy, and Journal of Energy Research.