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Optimization of Performance of Coarse Aggregate-Assisted Single-Slope Solar Still via Taguchi Approach

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ABSTRACT

In this experimental work, the energy efficiency and performance parameters of a coarse aggregate-assisted single-slope solar still were analyzed using Taguchi analysis. The preheated inlet saline water was sent to the solar still using thermal energy accumulated in coarse aggregate to enhance its productivity and energy efficiency. The daily distillate of the proposed model was observed to be about 4.21 kg/m^2 with the improved efficiency of around 32 %. Furthermore, the parameters that influenced the performance of the solar stills and their levels were identified using Taguchi analysis. The Signal to Noise (S/N) ratios of the coarse aggregate temperature, saline water temperature, glass temperature and energy efficiency were observed to be about 45.4 °C, 41.4 °C, 36.7 °C and 20.07 %, respectively. The results revealed that, the percentage difference between predicted and experimental values was observed to be about 1.6 %, 0.6 %, 1.5 % and 3.3 %, respectively. The optimization method confirmed that there was good agreement between the predicted and experimental values.

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1. INTRODUCTION

The demand for pure water is rising worldwide due to the growing density of population and industrial expansion. Desalination is the best and effective method to convert saline water into pure water. Solar still using the desalination process is known as one of the best low-cost effective techniques [1-4]. The performance of a solar still has mainly influenced the solar irradiation which has zero fuel cost. Even though some of the interior modifications have been made to the solar still, external heat sources are required to improve the heat transfer rate and productivity. The main objective of using this external heat source is that, there is a lot of unutilized heat energy emitted into the atmosphere. Therefore, sensible heat storage materials can be used to enhance the effectiveness of the solar still.

Yerzhan Belyayev et al. [5] employed a heat pump coupled solar still and found that, the daily yield of the proposed system improved by 80 %. The energy efficiency of this model was improved by 62 % with the daily yield of about 12.5 kg/m^2 during summer climate conditions. R. Dhivagar and S. Sundararaj [6] reviewed different types of solar still and concluded that the daily productivity of the solar still was improved by a higher saline water temperature. R. Dhivagar and S. Sundararaj [7] proposed the method of solar still assisted sensible heat storage material to preheat inlet saline water and achieved the enhanced efficiency of 28 % during higher sunshine hours. R. Dhivagar et al. [8] performed experiments on solar still using 4E analysis and obtained the improved energy and exergy efficiency rates of about 32 % and 4.7 %, respectively. Pounraj et al. [9] tested the hybrid photovoltaic thermal collector active solar still using a thermo-electric cooler with the improved efficiency of about 30 % than the simple conventional solar still. Modi and Modi [10] investigated the effectiveness of the double basin solar stills using cotton cloth and jute cloth and showed the improved yield rates of about 18.1 % and 21.5 % for jute cloth than the cotton cloth, respectively. Hardik K. Jani and Kalpesh V. Modi [11] conducted experimental works on the effectiveness of double-slope solar still using circular and square cross-sectional hollow fins. They improved the efficiency of the proposed model by 54.2 % (circular fins) and 26.8 % (square cross-sectional hollow fins), respectively. The results also revealed that, the higher productivity was achieved at a 1 cm water depth when compared to other different water depths. Dumka et al. [12] improved the effectiveness of the single slope solar still using sand filled in cotton bags as sensible heat storage material for different quantities of basin saline water. The result showed the overall improved efficiency rates of about 31.3 % (40 kg) and 28.9 % (50 kg), respectively. S. Joe Patrick Gnanaraj and V. Velmurugan [13] conducted experiments on different sensible heat storage materials such as fins, black granite, wick, reflector, and internal and external modifications and enhanced the effectiveness of the double-slope single and slope solar still systems by 58.4 %, 69.8 %, 42.3 %, 93.3 % and 171.4 %, respectively, when this proposed was compared to the conventional solar still. Sakthivel et al. [14] evaluated the performance of the single-slope solar still using jute cloth

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and enhanced the effectiveness and distillate by 8 % and 20 %, respectively, when compared to the effectiveness of the conventional solar still. Hidouri and Mohanraj [15] conducted experiments on heat pump-assisted solar still with different glass position configurations and improved the effectiveness by 84.5 %. They proved that, the glass positions in the solar still were playing a significant role in the daily distillate. S.W. Sharshir [16] conducted experiments on a solar still using graphite nanoparticles, film cooling and phase change materials. They showed that, the enhanced distillate of the proposed system was about 73.8 % when compared to the conventional solar still. Cai et al. [17] found that, the magnetic field would have considerable impact to reduce the surface tension of the water. Wang et al. [18] found that, the magnetic field was used to reduce specific heat capacity and enhance the evaporation rate through less surface tension.

2. TAGUCHI ANALYSIS

Taguchi analysis is a technique used for designing and performing experiments to investigate the dependency of the process upon several factors without having to run the process tediously and uneconomically using all possible combinations of values [19]. In Taguchi methodology, the desired design was finalized by selecting the best performance under the given condition. The orthogonal arrays were used for designing the solar still system due to its easy adaptability and simplicity [20, 21]. It is also recommended for the complex experiments that involve the number of factors and levels. The desired information can be attained with the minimum number of trails. In Taguchi method, the desirable signal value and undesirable noise value are determined at a signal-to-noise ratio. The S/N ratio is meant to be used as a measure of the effect of noise factor on the performance characteristic. S/N ratio is takes into account the variation in the reposed data and closeness of average response to targets. The equation for S/N ratio is performed based on the quality characteristics of the solar still parameters and is required to evaluate the experimental results.

Gupta and Singh [22] performed Taguchi and ANOVA analyses to determine the impact of parameters of the solar still yield. The outcome proved that, the saline water temperature was the significant parameter influencing the efficiency of the proposed system. Singh and Francis [23] analyzed the influence of saline water temperature and glass cover angle using Taguchi technique and found that both saline water temperature and inclination angle were found to be significant factors in increasing the effectiveness of the solar still. Verma et al. [19] employed Taguchi analysis to reveal the optimal set of factors of the single-slope solar still. The outcome of the experiment proved that saline water and glass were important factors in optimizing the productivity of the system.

The three types of S/N ratio are given as follows: i) smaller is better, ii) nominal is best and iii) larger is better [24]. The S/N ratios including larger is Better (LB) Smaller is Better (SB) and Nominal is Best (NB) are calculated through the following equation.

$$\frac{S}{N}\text{ratio for LB} = -10\log_{10}\left[\frac{1}{n}\sum\frac{1}{Y^2}\right] \quad (1)$$

$$\frac{S}{N}\text{ratio for SB} = -10\log_{10}\left[\sum\frac{Y^2}{n}\right] \quad (2)$$

$$\frac{S}{N}\text{ratio for NB} = 10\log\frac{Y}{S^2} \quad (3)$$

where, ‘Y’, ‘n, and ‘s’ are the response, the number of responses and variance of the observed data in the factor-level combination.

As derived from the above literatures, there are many sensible heat storage materials that have been used to enhance the effectiveness of the solar still. However, there is no experimental work related on coarse aggregate sensible heat storage assisted solar still and optimizing the performance parameters using Taguchi analysis. Hence, in this present work, the effectiveness of a solar still is investigated to determine the performance parameters that are influencing the distillate. The process parameters include coarse aggregate temperature, saline water temperature, glass temperature and efficiency. Solar irradiance, ambient temperature, relative humidity and wind velocity are considered as performance factors in this current study. The main objective of this work is to optimize the energy efficiency of the solar still using Taguchi analysis

3. EXPERIMENTAL

Figures 1 and 2 depict the schematic diagram and photographic view of the experimental setup. It contains a solar still, water storage tank, coarse aggregate, copper tube heat exchanger and distillate collection bottle. The solar still system was fabricated using galvanized iron sheet with the thickness of 2 mm. Then 50 kg coarse aggregate was used to extract the solar energy and the basin area of the solar still system was about 1 m^2. The size of the coarse aggregate was 5 mm.

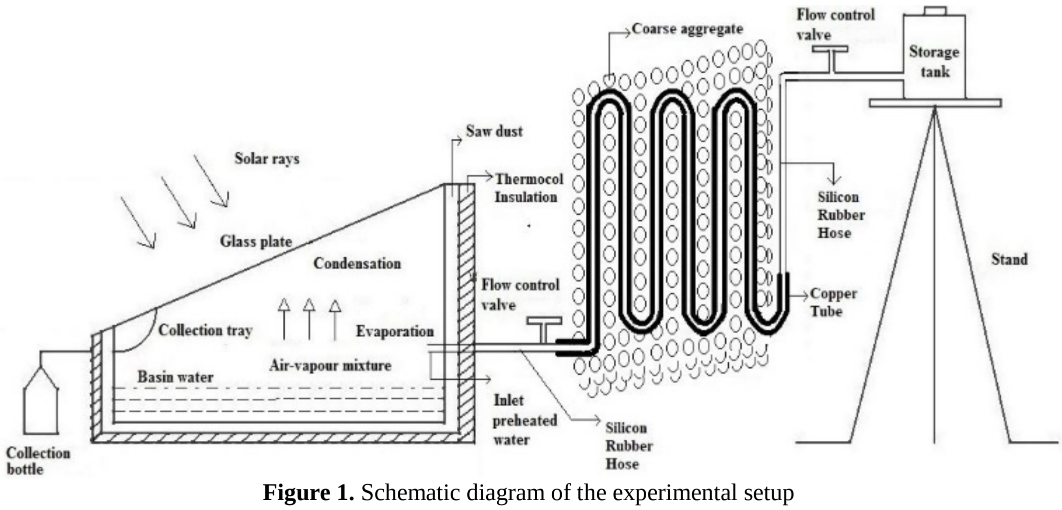

Figure 1. Schematic diagram of the experimental setup

Figure 2. Photographic view of the experimental setup

The solar still basin and the heat exchanger were painted with black for maximum solar irradiance absorption. The glass cover (3 mm thickness and 27° of inclination angle) was placed on the top of the solar still. The solar still system was placed into the sawdust and thermocol insulation chamber to reduce the thermal losses to the surroundings. Silicon rubber hose was connected to the solar still to transfer the feed preheated water from the water storage tank. Silica gel was used to stop the leakage of vapor from the solar still system to atmosphere. In this work, the coarse aggregate was heated during peak sunshine hours and the heat was transferred to the heat exchanger, preheating the saline water before sending into the solar still. The total surface of the heat exchanger was heated by the thermal energy accumulated in the coarse aggregate. A flow control valve was used to control the water flow and maintain the minimum water depth inside the solar still. For every one hour, the preheated saline water was allowed into the solar still using a flow control valve.

Different temperatures of the solar still system were measured using a K type thermocouple which was connected to the temperature indicator with the accuracy of about ± 0.2 °C. The solar irradiance was measured using a calibrated Kipp-Zonen pyranometer with the accuracy of about ± 5 W/m^2. A Vane type anemometer was used to measure the wind velocity of the air with the accuracy of ± 0.1 m/s. A measuring jar was used to measure the distillate from the collection tank. In this work, experiment observations were taken out from 9 AM to 6 PM during January – April 2020. The experimental setup was cleaned with fresh water once a week to remove the salinity and have accuracy.

Solar still performance parameters such as solar irradiance, wind velocity, ambient temperature and relative humidity influence the distillation process and their levels are summarized in Table 1. These levels were identified based on the general experimental trials. The solar irradiance range was between 250 and 860 W/m^2 during the experimentation. Accordingly, the three levels of solar irradiance were 264W/m^2, 532 W/m^2 and 856 W/m^2. Other three levels for Ambient Temperature (AT), Relative Humidity (RH) and Wind Velocity (WV) were identified along with the experimental works. L9 orthogonal array was generated using Taguchi's parameter design methodology and is shown in Table 2.

Table 1. Selected performance parameters and their levels

Parameter / Level	Solar irradiance (W/m^2)	Ambient temperature (°C)	Relative humidity (%)	Wind velocity (m/s)
1	264	26	45	0.7
2	532	29	50	2.4
3	856	34	60	3.7

Table 2. Taguchi L9 orthogonal array

Run	Performance parameters			
	SI (W/m^2)	AT (°C)	RH (%)	WV (m/s)
1	264	26	45	0.7
2	264	29	50	2.4
3	264	34	60	3.7
4	532	26	50	3.7
5	532	29	60	0.7
6	532	34	45	2.4
7	856	26	60	2.4
8	856	29	45	3.7
9	856	34	50	0.7

The performance parameters were repeated three times with the same conditions to validate the reliability of results obtained by the experiments. MINITAB is well suited for instructional applications and also powerful enough to be used as a primary tool for analyzing research data. In this work, MINITAB 19 version was used to optimize the conditions and analyze the results.

4. RESULTS AND DISCUSSION

The performance of the coarse aggregate-assisted single-slope solar still was investigated and the process parameters like coarse aggregate temperature, saline water temperature, glass temperature and energy efficiency were analyzed at different hours. Taguchi analysis was performed to establish the optimum values of the performance parameters such as solar irradiance, ambient temperature, relative humidity and wind velocity.

4.1. Thermal performance

The effect the solar irradiance and wind velocity is shown in Figure 3. The maximum solar irradiation of about 856.2 W/m^2 was observed during the noon hours and the minimum of about 45.1 W/m^2 during evening hours. However, the average solar irradiance was observed as 486.4 W/m^2 during the 10 hours of observations. The maximum and minimum wind velocities of about 0.7 m/s and 3.7 m/s were recorded, respectively during the experimental observations. However, it is noted that the wind velocity and solar irradiance have an average deviation from morning to evening during the experiments.

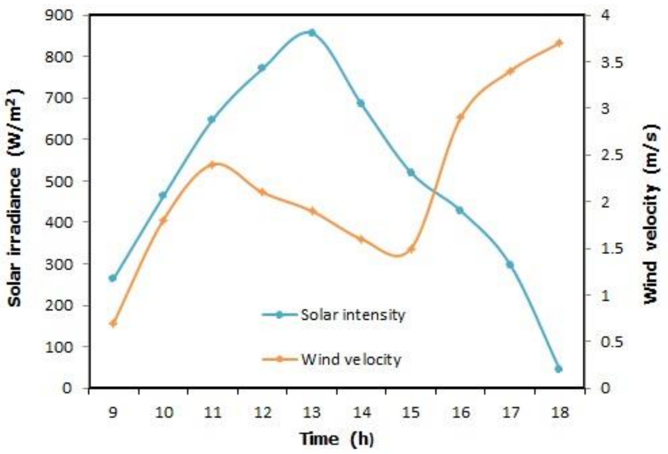

Figure 3. Effect of solar irradiance and wind velocity with time

Figure 4 shows the different temperatures at the still observed during the experimental observations. High temperature variation between the solar still and glass cover was used to improve the evaporation process and yield of the system. It is noted that, the maximum temperature of the coarse aggregate was about 66.1 °C at 13:00 hour which is higher than all other temperatures. It happens due to the accumulation of heat from the solar energy. The maximum ambient and glass temperature were about 34.2 °C and 52.4 °C at 13:00 hour. The gradual movement of wind velocity and the moisture content were applied to reduce the ambient and glass temperatures. Furthermore, the maximum saline water temperature was about 62.1 °C during noon hours. It is 24.2 % higher than saline water temperature for conventional still [6]. This happens due to the preheated saline water used as inlet in the solar still.

Figure 5 depicts the effect of hourly yield and efficiency with time. The rate of yield increases in a day time due to the accumulation of heat from the coarse aggregate. During the evening hours, it was reduced slowly with respect to the low solar irradiance and heat losses to the surroundings. This proposed solar still achieved 32 % of enhanced efficiency with the cumulative yield of about 4.21 kg/m^2/day. This solar still system has 4.98 % higher distillate than the previous experimental work done using jute cloth as an energy-storing medium [14].

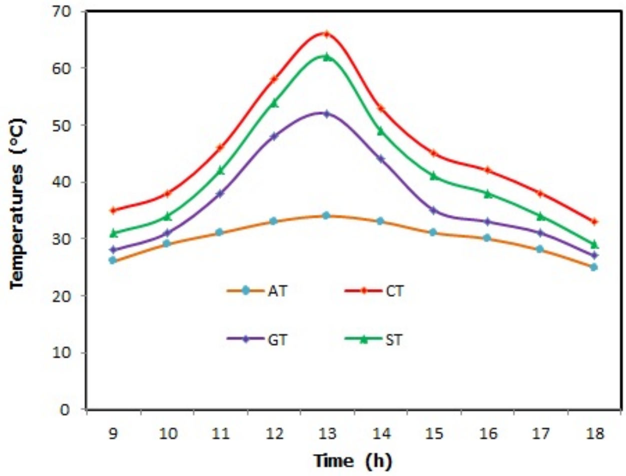

Figure 4. Effect of various temperatures with time

The energy efficiency was estimated as the quantity of thermal energy utilized for distillate to the quantity of solar irradiance observed in the solar still. Hence, the energy efficiency of the solar still was measured as follows [7]:

$$\text{Energy efficiency, } \eta_E = \frac{m_w \times h_{fg}}{A_s \times \sum I(t)_s \times 3600} \quad (4)$$

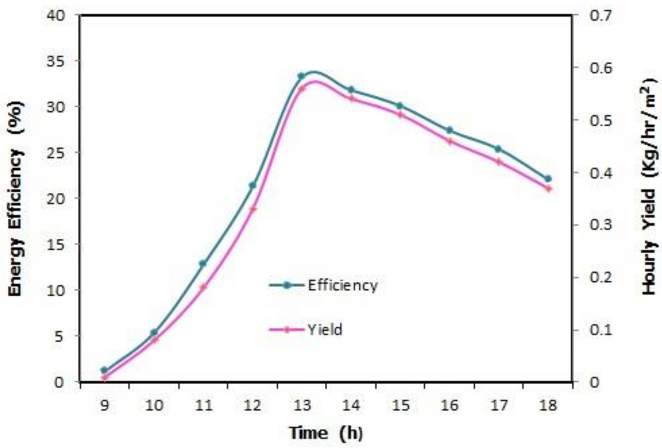

Figure 5. Effect of hourly yield and energy efficiency with time

4.2. Analysis of S/N ratio

The Taguchi method gives importance to the single to noise ratio to find the significant optimum value [25]. In this proposed solar system, the process parameters include coarse aggregate temperature, saline water temperature, glass temperature and energy efficiency. For this, the quality characteristic of coarse aggregate temperature was considered as "larger is better" in the still because of the temperature rise. Figure 6 shows the effect of S/N ratio of coarse aggregate with parameters. It was shown that the solar irradiance with higher influence was employed to enhance the heat accumulation rate during the experimentations. Relative humidity is the second important performance parameter that affects the temperature of the coarse aggregate effectively during the evening hours. This effect leads to enhancing the evaporation rate due to the temperature difference of systems and surroundings. The higher the S/N ratio parameter is the more significant the performance of the solar still [19].

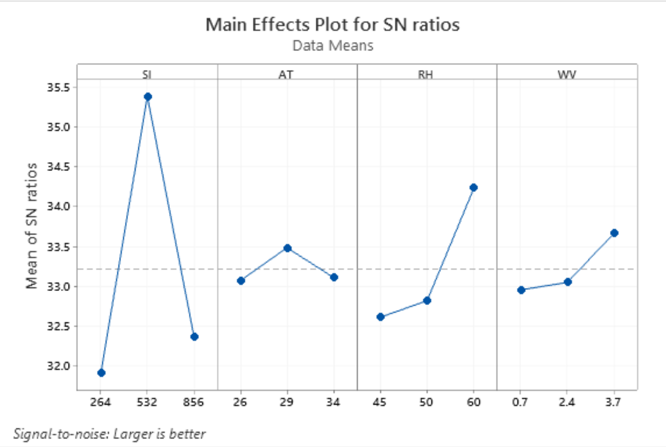

Figure 6. Effect of S/N ratio of coarse aggregate temperature

Figure 7 shows the effect of the S/N ratio of saline water temperature with parameters. Here, the quality characteristic of "larger is better" was assumed to know a factor which is mostly affecting the performance of the solar still. It was observed that solar irradiance with the major influence to affect the saline water temperature due to the maximum heat was accumulated by the coarse aggregate. The amount of moisture content (relative humidity) present in the ambient air also affected the saline water temperature after solar irradiance. As a result, the ambient temperature was affected which slightly decelerated the performance of the solar still system [20]. The higher the S/N ratio parameter the greater the importance of the performance of the solar still.

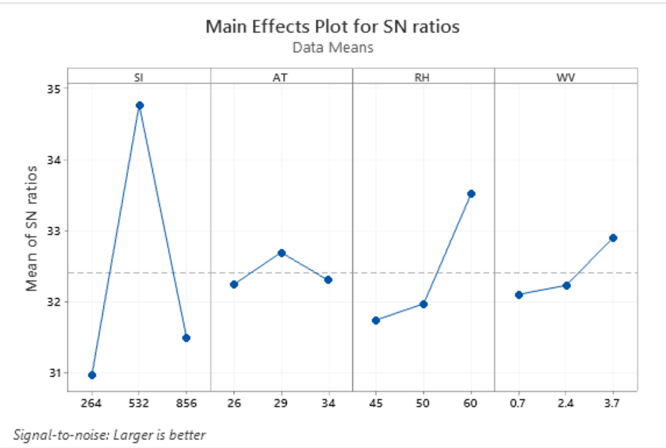

Figure 7. Effect of S/N ratio of saline water temperature

Figure 8 shows the effect of the S/N ratio of glass temperature with parameters. The quality characteristic called "larger is better" was assumed to determine the factor that mostly affected the performance of the solar still. Herein, solar irradiance and relative humidity were ranked first and second in affecting the glass cover temperature with major impact on the saline water temperature to enhance the rate of the hourly yield. The influencing rate of ambient temperature and wind velocity were comparatively lower than all other factors [22]. However, these two parameters are mainly related to the effect of solar irradiance and relative humidity. The higher the S/N ratio parameter is the greater the significance the performance of the solar still will be.

Figure 8. Effect of S/N ratio of glass temperature

Figure 9 shows the effect of the S/N ratio of energy efficiency with parameters. The quality characteristic known as the concept of "larger is better" was assumed to determine the factor mainly influenced by the system. It was shown that the solar irradiance and ambient temperature had the highest impact on the energy efficiency rating of the system. The accepted fact is that, the solar still productivity was mainly dependent on the effect of solar irradiance and the effect of ambient temperature during the noon hours [23]. Moreover, the influencing level of relative humidity and wind velocity is sharing their next positions. It may be differing from the different places. The higher the S/N ratio parameter the greater the significance of the performance of the solar still.

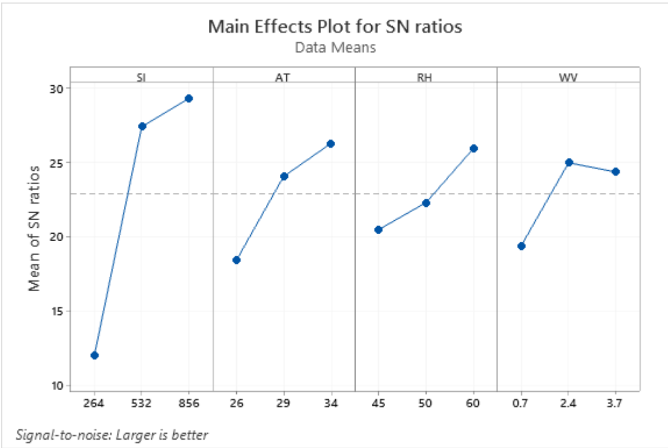

Figure 9. Effect of S/N ratio of energy efficiency

The S/N ratios for different levels of the parameters including coarse aggregate temperature, saline water temperature, glass temperature and energy efficiency were calculated. They were having the S/N ratios of 45.4 °C, 41.4 °C, 36.7 °C and 20.07 % respectively. In order to check the experimental results with optimal value, validation was required. The best operating factors were found and their value were compared to the predicted values using Taguchi method as shown in Table 3. The comparison shows that there is good agreement between predicted and experimental data. The percentage difference between predicted and experimental coarse aggregate temperature, saline water temperature, glass temperature and energy efficiency was 1.6 %, 0.6 %, 1.5 % and 3.3 % respectively. From this, the predicted results from optimization were more desirable than the experimental results.

Table 3. Experimental and predicted optimal conditions for process parameters

Results	Coarse aggregate temperature (°C)	Saline water temperature (°C)	Glass temperature (°C)	Energy efficiency (%)
Predicted	67.1	62.4	52.8	33.2
Experimental	66	62	52	32.1

5. CONCLUSIONS

Experimental investigation was performed on coarse aggregate assisted single slope solar still and the enhanced efficiency of about 32 % with a daily yield of 4.21 kg/m^2 was found. Furthermore, Taguchi analysis was carried out to identify the performance characteristics of the process parameters. The S/N ratios for different levels of the process parameters were calculated. Accordingly, coarse aggregate temperature, basin saline water temperature, glass temperature and energy efficiency were measured with the S/N ratios of about 45.4 °C, 41.4 °C, 36.7 °C and 20.07 % respectively. The percentage difference between predicted and experimental values of process parameters was 1.6 %, 0.6 %, 1.5 % and 3.3 %, respectively and the optimization method confirmed that there was good agreement between the predicted and experimental values.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

h_{fg}	Laten heat of vaporization (kJ/kg)
m	Productivity (kg)
A_s	Solar still area (m^2)
$I(t)_s$	Solar irradiance (W/m^2)
η_E	Energy efficiency (%)
Abbreviation	
AT	Ambient temperature
CT	Coarse aggregate temperature
GT	Glass temperature
RH	Relative humidity
ST	SSaline water temperature
WV	Wind velocity

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