SOLAR STILL PERFORMANCE FOR SEA WATER PURIFICATION: A STATISTICAL AND EXPERIMENTAL STUDY

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ABSTRACT

Sudden rise of fossil fuel prices and its scarce resources have caused the energy crises for the past few years. Current research has been focused primarily using renewable source of energy. The solar energy has been proved to be an economical alternative renewable energy used to extract the fresh water from sea water. The principle objective of the study is to purify the sea water by using solar energy. A pilot scale solar still has been designed, fabricated and optimized for maximum evaporation rate of model sea water. The various parameters such as water depth in still, average day temperature and average water temperature in still were studied experimentally and verified statistically though ANOVA (analysis of variance). It was found that the water temperature in the still is the most significant parameter that largely affects the evaporation rate. The fresh water with 240 mg/L dissolved salt has been extracted from the model sea water having dissolved salts of 35000 mg/L. The efficiency of a single basin solar still is improved up to 80 percent.

KEY WORDS: *Solar energy; Sea water desalination; Vaporization; Statistical analysis, experimental design.*

1. INTRODUCTION

Approximately 97% of the water is in the ocean, 2% of the water is stored as ice in polar region, and 1% is fresh water. This 1% fresh water is not fulfilling the demands of present world population[1,2]. Therefore fresh water is extracted from sea by conventional desalination methods using evaporation. Due to high latent heat of water, the evaporation is energy intensive and causes pollution due to burning of fossil fuels[3]. Membrane technology is emerging very rapidly in desalination to replace evaporation. Although it needs less energy to extract fresh water from sea water but still needs some energy to run the high pressure pumps. Due to limited reservoirs of conventional energy sources, the research has been focused to use alternative sources of energy for extraction of fresh water from sea.

Solar energy is getting more and more attention due to its very low operating cost and almost no environmental hazards[4]. Solar still is simple equipment that uses solar energy for producing distilled water in undeveloped regions that have access only to sea water, brackish or contaminated water. Solar stills are useful for small-scale remote applications. They are usually considered for removal of dissolved salts from water[5].The main working principle of solar still is to evaporate the water present in the still by means of solar radiations. The evaporated water free of contaminants is then condensed through condenser[6]. The reflecting mirrors can be installed on sides of solar still to concentrate the solar radiation on water basin to increase the rate of evaporation. The recycle of the preheated water through solar pump can further increase the distillate rate. The use of sun tracking system can also increase the efficiency of solar still, while showering of water over the glass cover maintains the temperature gradient and can produce more distillate. By applying the asphalt layer at the bottom of the basin which acts as a black body can increase the efficiency. Adjustable solar still angle can also increase the efficiency of solar still, through getting the maximum solar radiations by adjusting the angle according to the direction of the sun throughout the day. Multi stage solar collector can also be used in order to increase the surface area for heating the water. High thermal conductive material is recommended for manufacturing of solar still in order to reduce the heat losses[7,8].

For a maximum temperature range the solar system was accompanied with a collector panels and studied by Lawrence and Tiwari[9]. They observed that the reverse heat flow to the collector panel from the distillation unit was difficult to control during low

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intensity of solar radiation or low insulation periods, due to which the performance of the system was significantly affected. The thermal losses were significantly increased from the system at high operating temperatures, hence decreased the thermal efficiency of the system. Zaki et al.,[10] suggested that the yield obtained from inverted absorber double-basin solar still can be enhanced through reuse of latent heat, while the affect of solar radiation on the absorber was not considered. Hussain and Rahim[11] improved the performance of an evaporating unit by an aluminum sheet which has thermal insulation on the bottom and the top surface was painted black. The sheet was placed in the evaporating unit at distance of 20 mm below the surface of brackish water. The heat absorbed by the galvanized steel wall in the evaporator zone above the aluminum plate was utilized and hence improved the efficiency of the process.

Moreover, the variation of internal heat transfer from the basin of the solar still to the cover plate and external heat transfer from the cover plate to the atmosphere mainly depends upon longitude and latitude of the place, atmospheric temperature variation and variation in solar radiation intensity from morning to evening during a day[12]. When the reflecting mirrors were used on the vertical walls of the solar still instead of conventional still, the production rate was increased up to 86.2% for summer seasons and 22% for winter seasons.

Jabbar and Khalifa,[13] have studied that the cover tilt angle should be large in winter and it should be small in summer so that the productivity has been increased throughout the year. For the test side when the angle of latitude becomes large so the cover tilted should be large for the maximum productivity.

This paper presents the statistical analysis of purification of sea water by solar energy. Statistical analysis of experimental results and the optimum conditions are determined for process parameters such as water temperature, glass surface temperature, and water depth in solar still. The percentage contribution of these parameters and ANOVA (analysis of variance) model has been presented. Fresh water production from the sea water in the solar still has been observed in the real climatic conditions like air temperature, cold water temperature, glass surface temperature and solar radiation intensity.

2. EXPERIMENTAL SETUP

The experimental setup consist of feed tank, solar collector, solar still, product collecting trough and storage tank as shown in Figure 1. A known quantity of sea water was taken in the feed tank. Water flows from the feed tank in pipes through head and entered to the solar collector, where it is preheated and the temperature of water was raised. After passing through solar collector, pre-heated water entered into the solar still through splitter. The small pebbles were used for the uniform flow over the basin. The solar radiations passed through solar still and heat up the sea water due to which the water temperature has been increased. Due to high temperature the water got evaporated and moved upward. The water vapors were condensed on the tilted glass and fell down in the collecting trough from where the product water was collected in the product collecting tank. The temperature of glass cover and water was noted during each experiment after interval of half an hour. The amount of distillate was measured after each hour and experimental readings are noted for several days.

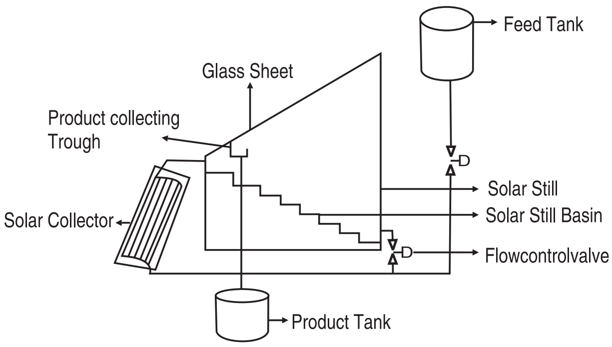

Figure 1: Experimental Sketch diagram

3. MATERIALS

For the construction of solar still such type of materials has been used which has the ability to withstand under harsh weather conditions. The materials should not degrade with hot sun and water. Such type of material should be selected that a bad test was not leave in fresh water. Different materials were used for fabrication of experimental unit as shown in Figure 2. The materials used were wood, galvanized Iron, glass, styrofoam, copper tube, PVC pipe, silicon sealant, glue, paint and digital thermometer etc. All materials were purchased from local market.

Figure 2: Experimental setup

Feed tank is made up of PVC and placed on a stand made from iron rods. The capacity of the feed tank is 0.025 m^3. Copper tube was used in solar collector for pre heating of water because it has high thermal conductivity. Copper tubes in the solar collector have 0.01 m in diameter and are used to preheat the incoming feed water. Copper tubes have been placed such that there was 2 inch distance between adjacent pipes so that total numbers of tubes are nine (9) with the heat transfer area of 0.29 m^2. Tubes and sheet were painted black in order to absorb heat. PVC pipe has 0.0127 meter diameter and is used to connect the different equipment.

The solar still has been made up of galvanized iron having basin area of 5.38 m^2, length 1 meter and width 0.5 meter, with steps of width 0.0833 meter and height of each step is 0.0508 meter. Front height of the still is 0.30 meter and back height is 0.64 meter. Wood was used to cover the solar still and prevent it from harsh environment (corrosion, erosion) and heat losses from still. The dimensions of the wooden box are length 1 meter, width 0.50 meter and height 0.10 meter. Galvanized Iron sheet has been placed in wooden box of the solar still to absorb more solar radiations and offer resistant to the harsh environment. Styrofoam having thickness 0.038 meter has been placed between metal still and wooden box to prevent heat losses from the still to the environment. The glass was placed at the top of the solar still and solar collector having area of 0.5 m^2 and thickness of the glass was 0.004 m through which the solar radiations passed and heat up the water inside the solar still and solar collector. Thermometers were used to measure the temperature of the water in the basin of the still and the surface of the glass. The product collecting trough was made from metal sheet, and fitted in such a way to collect water from the glass.

4. RESULTS AND DISCUSSION

The research work consisted of two main parts. The "one-factor-at-a-time" approach was presented in the first part in order to find the significant parameters that significantly affect the fresh water recovery. The result of "one-factor-at-a-time" approach was then confirmed through "design of experiments" analysis.

4.1. One-factor-at-a-time approach for water purification

In this approach the effect of one factor was evaluated while all other remaining factors were kept constant. The selected factors were water average temperature and water depth in solar still.

4.1.1. Effect of water and glass surface temperature

The main objective was to calculate the performance of solar still for different temperature of basin

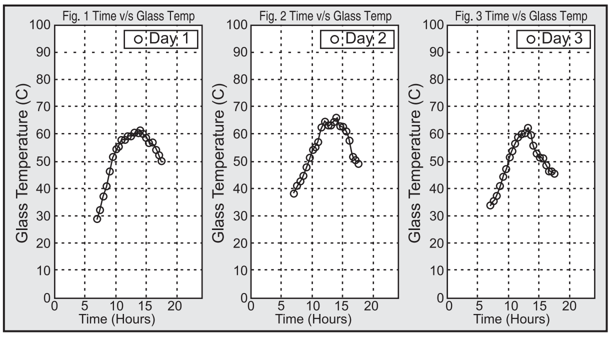

Figure 3: Glass temperature curves for three days

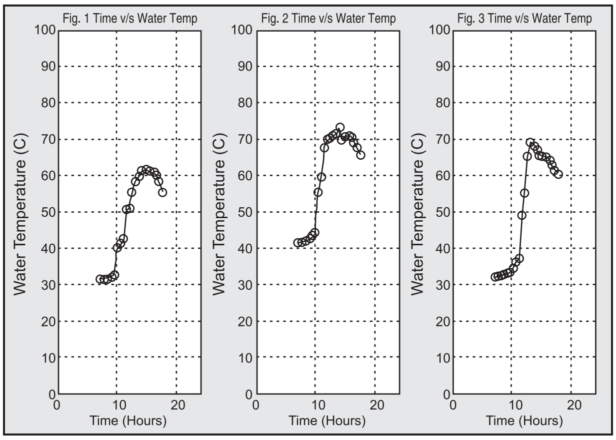

Figure 4: Water temperature curves for three days

water. For this purpose experiments were conducted on daily basis and temperature of basin water and glass were noted, along with the amount of distillate obtained. The experimental data of three days in which the glass and water temperatures have been plotted at different interval of time and have been shown in Figures 3 and 4.

The first day was a bright sunny day. As shown in Figure 4, the highest temperature of water obtained at that day was 61.5ºC, while according to the Figure 3 the highest temperature of glass was 61.2ºC. The amount of average distillate on the same day was 0.001910 m^3. At the 2nd day temperature was high from the morning, highest temperature of water obtained at that day was 73.3ºC, and that of glass was 65.8ºC. On the second day the amount of average distillate was 0.002695 m^3. The observation on the third day was that the temperature of water and glass was low at the morning and increased with time. Highest temperature of water obtained was 69.1ºC, and that of glass was 62.2ºC. On third day the amount of average distillate obtained was 0.002385 m^3.

The average temperature for each day was obtained from the average of the minimum and maximum temperatures of that day. The daily average temperature has been mentioned in Table 1. So it is concluded that when the average temperature of water and glass was increased, the amount of purified water increased. Murugavel et al.,[14] have also observed the same results.

4.1.2 Effect of the water depth in solar still

To study the effect of water depth on the purification rate of water, the depth of water in the solar still was changed in two steps i.e. 0.1016 m and 0.2032 m. At the first day, the purified water obtained was 0.00192 m^3 for water depth of 0.1016 m. The amount of purified water decreased to 0.00190 m^3 when the water depth was increased to 0.2032 m. The same results were also obtained on the second and third days. The results of all three days are shown in Table 3. From the results shown in Table 3, it can be seen that the production of distilled water has inverse relation with water depth in the solar still. Phadatare and Verma[15] have also presented the same results in their study.

4.2. Design of experiments approach through statistical analysis for water purification

For finding the significant factors, the first step was to perform the screening of experiments for the purification of water through solar energy in order to identify the factors that significantly influence the response. From the (Design Expert 8.0.3 trail version) software application in order to find the significant factors, taking the average temperature of the three days and the two levels of water depth in still which are shown in the below Table 2. The Product (Fresh water) after purification and solar distillation was obtained in experimental design matrix as shown in Table 3.

Different runs were performed for the main factors average water temperature and water depth in solar still in order to study the effect of these factors and their interaction on the purified water obtained during experiments. The design expert was applied on the Table 2 and the response was taken from the Table 3.

The Design expert was also used to find the percentage contribution of each factor and their interactions. The percentage contribution was given in Table 4. It has been observed from Table 5 that the main factors water temperature and water depth in solar still have more percentage contribution as compared to their interactions.

Table 1: Average daily water temperature

S. No.	Days	Water Temperature ºC		Day Average Temperature ºC
		T_{min} ºC	T_{max} ºC	
1	1st	31.6	61.5	46.55
2	2nd	41.4	73.3	57.35
3	3rd	32.1	69.1	50.6

Table 2: Natural and codified values of parameters (Design Matrix)

S.No.	Factors	Natural values			Codified values		
		Min	Avg.	Max	Min	Avg.	Max
1.	Water Temperature (ºC)	46.5	50.6	57.4	-1	0	+1
2.	Water Depth in Still(meters)	0.1016	—	0.2032	-1	—	+1

Table 3: Experimental design matrix

Run	Water average temperature ºC	Water depth (meters)	Amount of purified water m^3
1	57.35	0.1016	0.00270
2	57.35	0.2032	0.00269
3	50.6	0.1016	0.00240
4	46.55	0.1016	0.00192
5	46.55	0.2032	0.00190
6	50.6	0.2032	0.00237

Table 4: Percentage contribution for Design Matrix (3)

Term	df	Sum of squares	Mean square
Water average temperature	2	6.253+E005	3.126+E005
Water depth in still	1	600.00	600.00
AB	2	100.00	50.00
Residuals	0	0.000	

Table 5: ANOVA Model for purified water

Response 1 Purified water

ANOVA for selected factorial model

Analysis of variance table [classical sum of squares – Type II]

Source	Sum of squares	df	Mean square	F value	P-value Prob>F	
model	6.259E+005	3	2.086E+005	4172.67	0.0002	Significant
A-water average temperature ºC	6.253E+005	2	3.126E+005	6253.00	0.0002	
B- water depth	600.00	1	600.00	12.00	0.0742	
Residual	100.00	2	50.00			
Col total	6.260E+005	5				

The Analysis of variance for the experimental design matrix Table 3 having two level of factorial design for purified water has been presented in Table 5.

The model indicates that it is significant. There is small noise factor which shows that model is accurate. The ANOVA (analysis of variance) model shows that water average temperature was more significant compared to water depth in solar still.

The design expert software was used to found out the significant factors as shown in Figure 5 as it gives the half normal plot for the experimental design matrix. The water average temperature and water depth in the still are represented by A and B respectively in Figure 5. The half normal plot shows that water temperature was more significant as compared to water depth in the solar still and its combined interaction. The Residuals verses predicated plot is shown in Figure 6.

It is observed from Figure 6 that all residues lie within the red lines, which shows that residuals are uniformly distributed. It also shows that there was no outlier in the experimental data and the uniformly distribution of the experimental data indicates that the proposed model was satisfactory to fit the experimental data. The residual plots against each factor are shown in Figures 7 and 8.

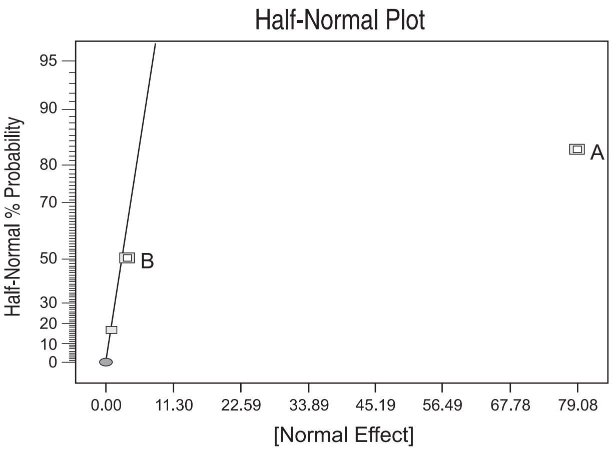

Figure 5: Half Normal Probability Plot for Matrix.3

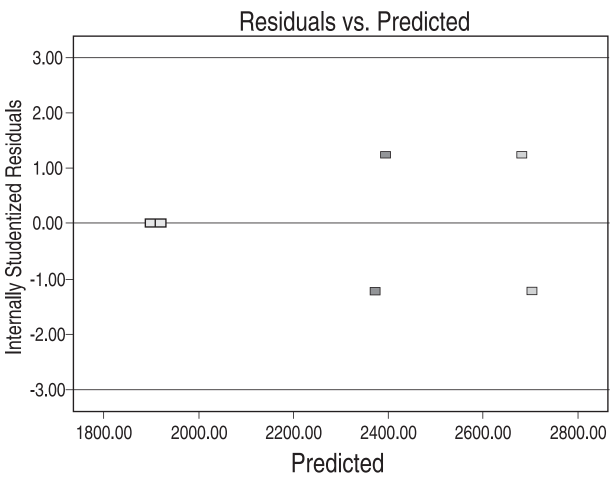

Figure 6: Predicted responses versus residuals

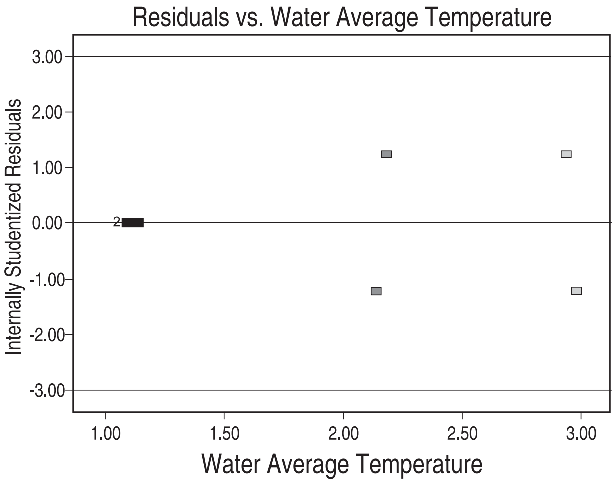

Figure7: Residuals versus water average temperature

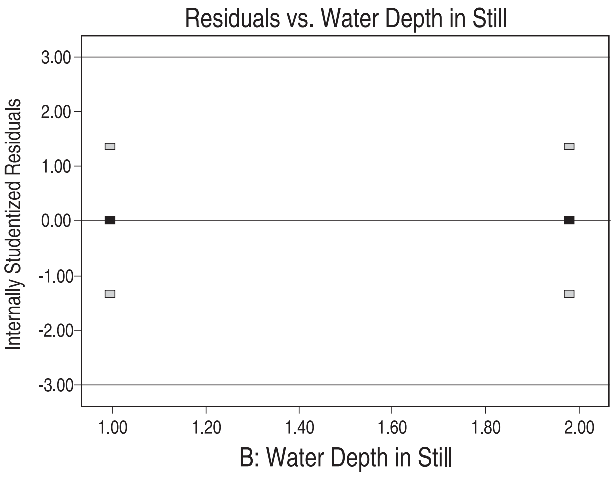

Figure 8: Residuals versus water depth in still

Figure 7 shows that there is no outlier in the experimental data indicating that the proposed model is reasonably accurate for the average temperature of water in order to get the required response. Furthermore the outliers were checked in the residuals versus water depth in still as shown in Figure 8. All the data points are vertically spread indicating that there was no outliers in the data and the proposed model was satisfactory with respect to the water depth in the still. The contour response for the design matrix has been shown in Figure 9.

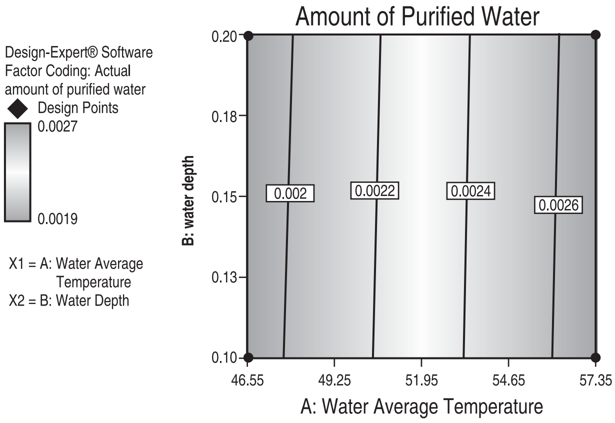

Figure 9: Counter plot of amount of purified water

From Figure 9 it is shown that the maximum predicted amount of purified water was (0.00269 m^3) at maximum average water temperature (57.35ºC) and when the water depth in the solar still was 0.1016 meter, while the minimum amount of purified water was 0.002 m^3 obtained at average water temperature (46.55ºC) and water depth was 0.2032 meter.

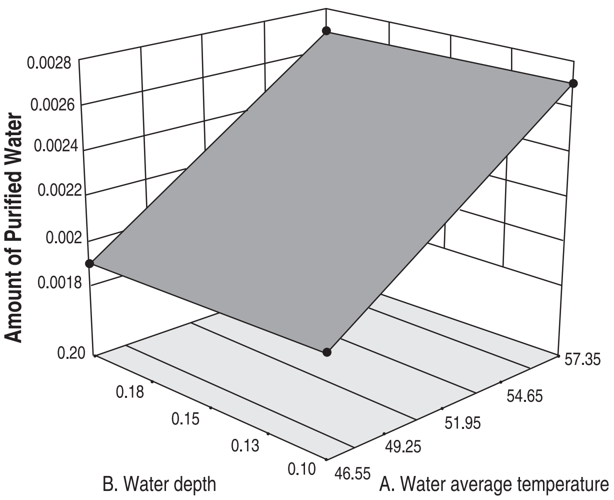

Fig.10. Response Surface plot of amount of purified water

The response surface plot for the design matrix (Table 3) has been shown in the Figure 10. The response surface plot also validate the counter plot and shows that the maximum amount of purified water was obtained at the maximum average water temperature and at minimum water depth in the solar still.

5. CONCLUSION

In the current work process parameters in a solar still distillation were examined experimentally and verified statistically. Based on the one factor-at-a-time approach the amount of water purified in solar still varies linearly as a function of water and glass surface temperature and inversely as a water depth in the solar still. The one factor-at-a-time approach provides an insight on the interaction effects of various factors. In order to take into account the combined effect of factors screening experiments were performed. The amount of purified water increases significantly with the average water and glass surface temperature. (Design Expert 8.0.4 Trial version) software was employed to determine the significant factors. The Initial total dissolved solids (TDS) concentration in the feed was 35000 mg/L while in the product water is 240 mg/L. The daily output from the solar distillation plant was increased from the 0.0015 m^3/day/m^2 to 0.0027 m^3/day/m^2 with the help of flat plate collector working as a preheating and styrofoam layer working as insulation to prevent heat losses. Thus the efficiency of a single basin solar still was improved up to 80 percent. The maximum amount of purified water (0.0027 m^3) was obtained at maximum average water temperature (57.35ºC) and minimum water depth at 0.1016 meter.

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