Predicting and Analyzing the Efficiency of Portable Scheffler Reflector By Using Response Surface Method

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Abstract

Portable Scheffler reflector (PSR) is an important and useful mechanical device used solar energy for the numerous applications. The present work consists of 2.7 square meter scheffer reflector used for the domestic application in Indian context such as water heating. The parameters such as the position of the PSR surface with respect to the sun i.e. tilting angle (AR),the processing timing (TM) measured in 24 Hr clock and the water quantity (WT) are considered as a independent parameters. The parameter related with the PSR performance is the efficiency of the PSR (EFF).The response surface methodology (RSM) was used to predict and analyze the performance of PSR. The experiments conducted based on three factors, three-level, and central composite face centered design with full replications technique, and mathematical model was developed. Sensitivity analysis was carried out to identify critical parameters. The results obtained through response surface methodology were compared with the actual observed performance parameters. The results show that the RSM is an easy and effective tool for modelling and analyzing the performance of any mechanical system.

Keywords : Portable Scheffler reflector; Response surface method; Optimization; Sensitivity Analysis; desirability function.

1 Introduction

German scientist Wolfgang Scheffler has devised a parabolic reflector set-up to harness solar energy using low cost set-up which can be used in rural areas in India. A concentrating primary reflector tracks the movement of the Sun, focusing sunlight on a fixed place. The focused light heat a very

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large pot, which can be used for heating, steam generation, cooking, baking breads, and water heating .The Scheffler reflector can be used for the supply of hot water for domestic purposes. These systems can have one water storage tank which performs dual function of absorbing solar radiation and preserving heat of water. Many methods are suggested to keep water temperature at a satisfactory level. Among them, the use of a selective absorber that reduces radiation thermal losses and double glazing, transparent insulation, and inverted or evacuated absorber to suppress convection thermal losses are suggested methods that preserve water storage heat. In the literature, few works are referred to Scheffler reflector with cylindrical water storage tanks mounted at focal point. The use of Scheffler reflectors can result in effective water heating by using the non-uniform distribution of solar radiation on the cylindrical absorber surface. In most of these systems the part of the cylindrical absorber is thermally insulated in order to reduce storage. In the present work experimental study of Scheffler reflector water heater (SRWH) consisting single storage tank as an absorber mounting in side curved reflector trough has been carried out. The solar reflector of 2 liter per day capacity is designed .In this design the thermal insulation on storage tank is not provided to lower down the cost of water heater and for its wide applications in domestic sector.Solar water heating system of this type defer to flat plate solar collector in design and operation as it consists of an unit with dual operation, to absorb solar radiation and to preserve the solar heat, instead of the absorbing solar radiation and the heating only the circulating fluid. The designed model for experimentation is shown in Figure. 1.

The solar reflector of 2 liter per day capacity is designed with dish diameter of $2.7m^2$. The storage tank painted black is so positioned that its periphery lies on the focus of the parabolic reflector. Non return valve was fitted at the inlet line and air vent, pressure relief valve at the outlet line. For analysis and testing purpose, Al-Cr thermocouples were located at different positions in the heater. This type of compact solar water heater is simple in design, low in cost, easy in operation and maintenance, easy to install and of high efficiency compared to flat plate collectors and tubular type integrated collector storage systems. The storage tank has an entrance for the water at the top of one side of it and an exit at the bottom of the other side of it. Akachukwu Ben Eke[1] has used a flat plate surface solar collector of dimension 0.5 square meter, hinged on a horizontal support for quick adjustment of inclination from 0 to 90° was fabricated, marked sout atone degree intervals on a telescopic leg graduated in degrees. Measurement of the solar radiation, varying degrees of inclination were taken between 12:00 noon and 2:30 pm for 4 days at clear sky hours, within the week of the year. The analysis indicated that when a flat surface was located at the predicted optimum angle of inclination for each month of the year, an average annual increment of 4.23 % solar radiation intensity was achieved, when compared with the yearly average solar radiation intensity harnessed by the same flat plate collector on horizontal position, and under the same condition. This percentage increase amounted to annual average solar energy gain of 370,670 MJ/m^2, at no extra-cost, other than positioning the solar collector at the identified optimum angle of inclination. Comparison of the measured and calculated optimum values of angle of inclination of a flat plate surface for trapping maximum solar radiation intensity for each month of the year indicated a high correlation with R2 of 0.97. It was found that solar flat collector can be fixed permanently in Zaria at 22.5°. Lubna. B. Mohammed et. al [2] has used a nonlinear Autoregressive Exogenous (NARX) model to predict hourly solar radiation in Amman, Jordan. This model was constructed and tested using MATLAB software. The performance of NARX model was examined and compared with different training algorithms. Meteorological data for the years from 2004 to 2007 were used to train the Artificial Neural Network (ANN) while the data of the year 2008 were used to test it. The MarquardtLevenberg learning algorithm with a minimum root mean squared error (RMSE) and maximum coefficient of determination (R) was found as the best in both training and validation period when applied in NARX model. Different training algorithms were compared to select the best suited algorithm. The MarquardtLevenberg learning algorithm with a minimum root mean squared error (RMSE) and maximum coefficient of determination (R) was found as the best in both training and validation period when applied in NARX model C. Dorflinget.al. [3] has reported the experimental data from, and numerical modelling of, plastic solar collectors fabricated from a novel thermoplastic extrudate. The extrudate, termed as micro capillary film (MCF), consists of an extruded flexible, plastic, film with a parallel array of hollow capillaries running along the films length. Experimental investigations were carried out on two laboratory scale solar collectors, illuminated with an infrared lamp, to determine the effects that different process fluids, glazing layers and collector backgrounds had on the overall heat recovery of the collector. The experiments also examined the effects that fluid flow rate, collector length and capillary wall thickness had on the heat recovery. Heat recovery of a similar order of magnitude to commercially available collectors was attained. A finite difference model was developed to calculate the temperature gain and the heat recovery of these solar collectors as a function of design and operating parameters. This model was successfully validated against experimental data, and was able to quantitatively predict the performance of these devices. Results from this investigation suggest that MCFs perform heat exchange duties of this type well, with the potential to make a low-cost, lightweight, mechanically flexible, solar collector.Fatigun A.T et. al [4] has studied the effect of tube spacing on the performance of a Flat Plate Collector (FPC). A comparative study of the performance of two FPC with average adjacent tube spacing of 20 cm and 11 cm was carried out for five days in July, 2011.Comparison shows that both the inlet and the outlet temperature of collector B with adjacent tube spacing of 20 cm were persistently higher than that of Collector A with adjacent tube spacing of 11 cm for most hours of the day. Efficiency 0f 10% and 21% was recorded for collector A and B respectively on day 1 while the values dropped to almost half on day 2 and to less than 5% on days 3, 4 and 5 for both collectors due to frequent cloud cover and rain. It can be inferred that adjacent tube spacing has significant effect on the performance of a flat plate collector[5]

2 Experimentation

From the literature review and the previous work done, tilting angle of the reflector (AN), processing time (TM), and water quantity (WQ), were selected as process parameters for this study. The efficiency of the reflector (EFF) is the dependent parameters.

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2.1 Finding working limits of the independent parameters

Following Tables 1 shows the various parameters were used to carry out the trial runs to analyse the performance of PSR. This was carried out by varying one of the factors while keeping the rest of them at constant values. The working range of each process parameter was decided upon by requirement of the user and the seasonal variation in India. Figure 1 and Figure 2 shows the experimental set up and the flow of energy form the sun to the object [6–10].

Figure 1: Experimental setup for the performance analysis of the PSR

Table 1: Important process parameters and their levels for PSR

Independent Parameters	**Level**		
	1	**2**	**3**
Tilting Angle (AN) Degree	20	50	80
Processing Time (TM) 24 Hr Clock	9.00	14.00	17.00
Water Quantity (WQ) (liter)	1	2	3
Dependent Parameter			
Efficiency of the PSR (EFF)			

2.2 Conducting experiments

The various experiments were conducted to analyze the performance of PSR. Three factors with three levels were selected for experimentation.The design matrix chosen to conduct the experiments was a central composite face centered design [11], which is listed in Table 2.The Efficiency is given by the following equation 1.

$$Efficiency = \frac{Output}{Input} = mc_p \bigtriangleup T/R * A = mc_p(T2 - T1)R * A \qquad (1)$$

Where,
A = Area of Flat PSR =2.7 m2
T1 = Temperature of water at inlet in ℃,
T2 = Temperature of water at outlet in ℃,
Mass of water taken in the storage tank = 1,2and 3 Lit. or mm^3,
Specific heat of water =4.182 kJ/kg K
ρ = Density of water =1000 kg/m^3
R= Radiation fall on the surface in W/m^2

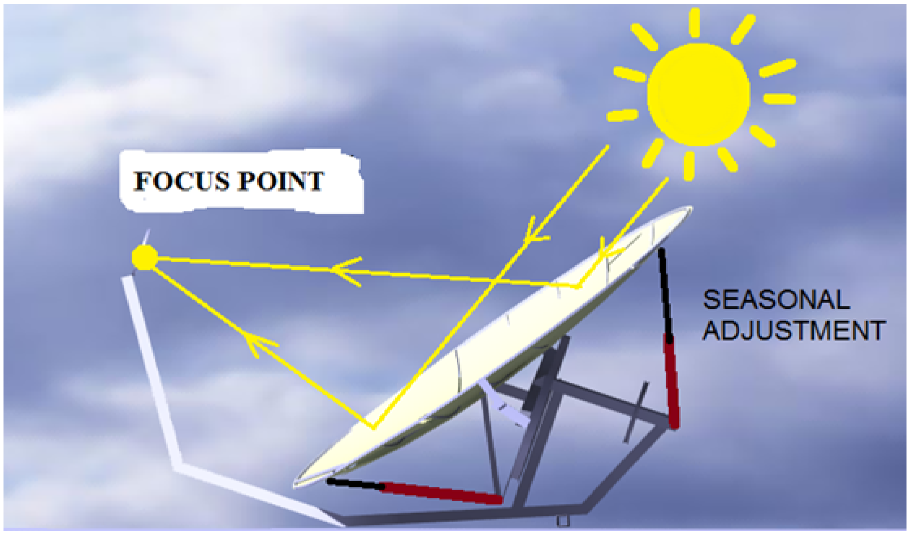


Figure 2: Flow of solar energy from the sun to the object

3 Development of Mathematical Model

3.1 Response Surface Method

Response surface methodology (RSM) is a collection of mathematical and statistical technique useful for analyzing problems in which several independent variables influence a dependent variable or response and the goal is to optimize the response. In many experimental conditions, it is possible to represent independent factors in quantitative form[12]. The second order polynomial (regression) equation used to represent the response surface Y is given by as given in Eq.(2).

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{i,j} x_i x_j + \varepsilon_r \quad (2)$$

In order to estimate the regression coefficients, a number of experimental design techniques are available. In this work, central composite face centered design Table 4 was used which fits the second order response surfaces very accurately. Central composite face centered (CCF) design matrix with the star points being at the centre of each face of factorial space was used so $\alpha = 1$. The upper limit of a factor was coded as +1, and the lower limit was coded as 1. All the coefficients were obtained applying central composite face centered design using the MINITAB16 statistical software package. After determining the significant coefficients (at 95% confidence level), the final model was developed using only these coefficients and the final mathematical model to estimate the efficiency of the PSR. The equation is as follows:

$$EFF = -0.815071 - 0.015013 * AN + 0.238045 * TM - 0.0089744 * WQ - 8.79375E^{-05} * AN^2$$
$$-0.00888 * TM^2 - 0.0199586 * WQ^2 + 0.000242523 * AN * TM + 0.00193111 * AN * WQ \quad (3)$$

3.2 Checking Adequacy of the Model

The adequacy of the developed model was tested using the analysis of variance(ANOVA) technique andthe results of second order response surface model fitting in the form of analysis of variance (ANOVA) are given in Table 3. The determination coefficient (R^2) indicates the goodness of fit for the first model. In this case, the value of the determination coefficient (R^2=0.9784) indicates that only less than 2% of the total variations are not explained by the model. The value of adjusted determination coefficient (adjusted R^2 =0.9873) is also high, which indicates a high significance of the model. Predicted R^2 is also in a good agreement with the adjusted R^2. Adequate precision compares the range of predicted values at the design points to the average prediction error of the value of probability >F in Table 3 for model is less than 0.05, which indicates that the model is significant.

In the same way, tilting angle (AN), processing time (TM) and the water quantity(WQ), interaction effect of tilting angle (AN) and processing time (TM), interaction effect of tilting angle (AN) and the water quantity (WQ) and second order term of tilting angle (AN), processing time (TM) and the water quantity (WQ) have significant effect. The residuals plots for the efficiency of PSR are as shown in Figure 3.

Table 2: Experimental design matrix and the results

Run	Coded Value			Coded Value			Efficiency
	AN	TM	WQ	Angle	Time	Water QTY	
1	1	1	1	20	9	1	0.349553
2	1	1	1	20	9	1	0.395687
3	1	1	1	20	9	1	0.490329
4	1	2	2	20	14	2	0.522829
5	1	2	2	20	14	2	0.557652
6	1	2	2	20	14	2	0.597398
7	1	3	3	20	17	3	0.381894
8	1	3	3	20	17	3	0.385971
9	1	3	3	20	17	3	0.408028
10	2	1	2	50	9	2	0.264168
11	2	1	2	50	9	2	0.271569
12	2	1	2	50	9	2	0.309269
13	2	2	3	50	14	3	0.437077
14	2	2	3	50	14	3	0.527566
15	2	2	3	50	14	3	0.532584
16	2	3	1	50	17	1	0.369065
17	2	3	1	50	17	1	0.411392
18	2	3	1	50	17	1	0.444216
19	3	1	3	80	9	3	0.399903
20	3	1	3	80	9	3	0.410950
21	3	1	3	80	9	3	0.393027
22	3	2	1	80	14	1	0.494953
23	3	2	1	80	14	1	0.522392
24	3	2	1	80.	14	1	0.590448
25	3	3	2	80	17	2	0.574735
26	3	3	2	80	17	2	0.565847
27	3	3	2	80	17	2	0.563538

Table 3: ANOVA results for the efficiency of PSR.

Source	DOF	Square SS	Adjusted SS	Mean Square	F Value	ρ Value Probability >S
Regression	8	0.225799	0.225799	0.028225	17.16	0.000
Linear	3	0.075917	0.074646	0.024882	15.13	0.000
AN	1	0.014484	0.010586	0.010586	6.44	0.020
TM	1	0.059809	0.058199	0.058199	35.39	0.000
WQ	1	0.001624	0.000540	0.000540	0.33	0.573
Square	3	0.115780	0.128422	0.042807	26.03	0.000
AN*AN	1	0.038205	0.038112	0.038112	23.17	0.000
TM*TM	1	0.072395	0.090349	0.090349	54.94	0.000
WQ*WQ	1	0.005179	0.002134	0.002134	1.30	0.269
Interaction	2	0.034102	0.034102	0.017051	10.37	0.001
AN*TM	1	0.016719	0.004668	0.004668	2.84	0.108
AN*WQ	1	0.017383	0.017383	0.017383	10.57	0.004
Residual Error	19	0.031247	0.031247	0.001645		
Pure Error	19	0.031247	0.031247	0.001645		
Total	27	0.257047				
Std deviation	0.0405537			R^2	0.9784	
Press	0.0640674			Adjusted R^2	0.9873	
				Predicted R^2	0.9608	

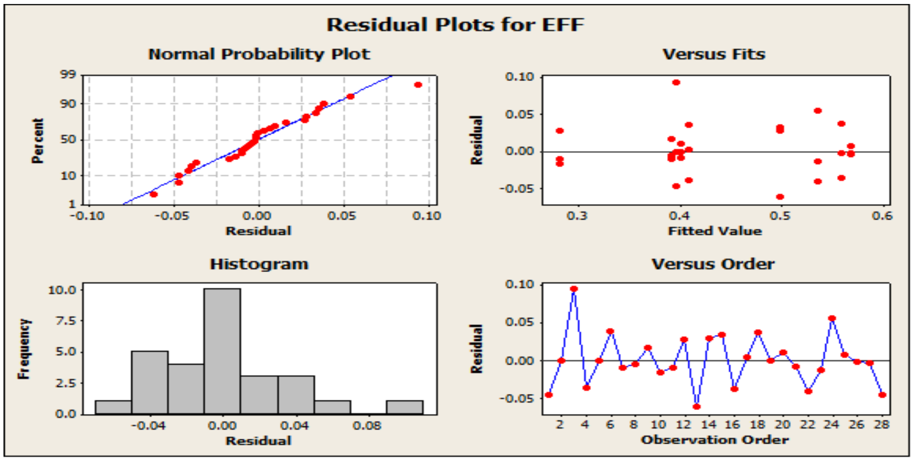
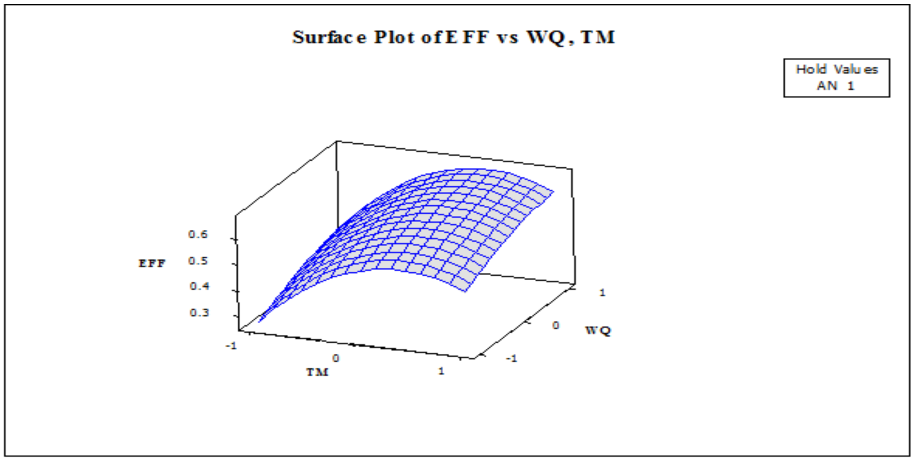


Figure 3: Residual plots for the Efficiency of PSR (EFF) response

3.3 Optimizing parameters

Contour plots show distinctive circular shape indicative of possible independence of factors with response. A contour plot is produced to visually display the region of optimal factor settings. For second order response surfaces, such a plot can be more complex than the simple series of parallel lines that can occur with first order models. Once the stationary point is found, it is usually necessary to characterize the response surface in the immediate vicinity of the point by identifying whether the stationary point found is a maximum response or minimum response or a saddle point. To classify this, the most straightforward way is to examine through a contour plot. Contour plots play a very important role in the study of the response surface. By generating contour plots using software for response surface analysis, the optimum is located with reasonable accuracy by characterizing the shape of the surface. If a contour patterning of circular shaped contours occurs, it tends to suggest independence of factor effects while Elliptical contours as may indicate factor interactions. Response surfaces have been developed for both the models, taking two parameters in the middle level and two parameters in the X and Y axis and response in Z axis. The response surfaces clearly reveal the optimal response point. RSM is used to find the optimal set of process parameters that produce a maximum or minimum value of the response. In the present investigation the process parameters corresponding to the efficiency of the PSR are considered as optimum (analyzing the contour graphs and by solving Eq.2 Hence, when these optimized process parameters are used, then it will be possible to attain the maximum response. Fig.4 presents three dimensional response surface plots for the various responses obtained from the regression model. The optimum response is exhibited by the apex of the response surface. Fig.5(a) exhibits almost a circular contour, which suggests independence of factor effect namely water quantity and processing time. It is relatively easy by examining the contour plots (Figs.5(b,c), that changes in the response are more sensitive to changes in titling angle than to changes in water quantity and processing time.



Response Optimization

Table 4: Optimization table

Goal	Lower	Target	Upper	Weight	Important
Maximum Efficiency	0.45	0.600	0.600	1	1

Global Solution

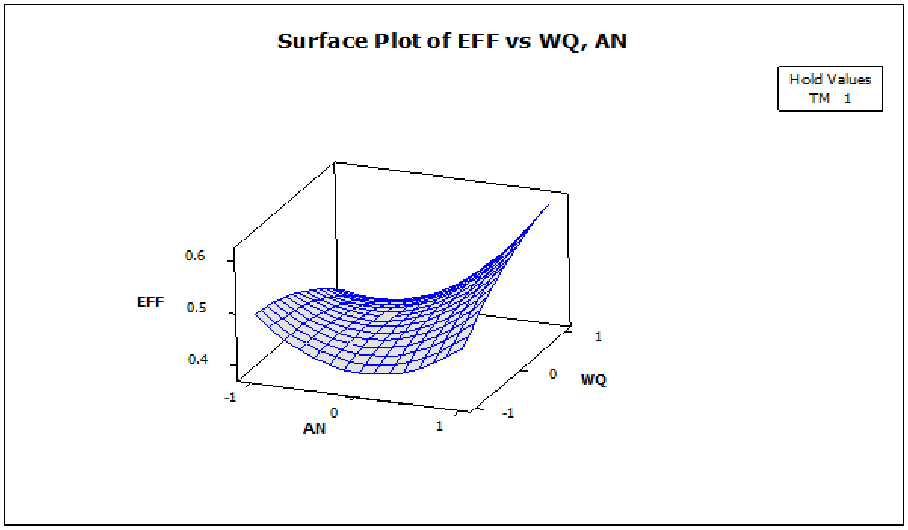
AN = 20; TM = 12.9362;WQ = 1

Predicted Responses

EFF = 0.586

Desirability = 0.903949

Composite Desirability = 0.760328



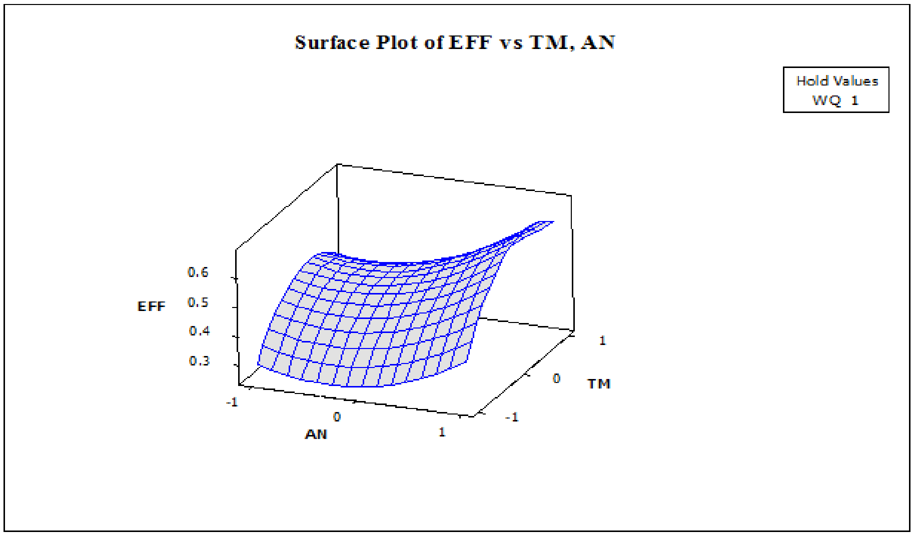
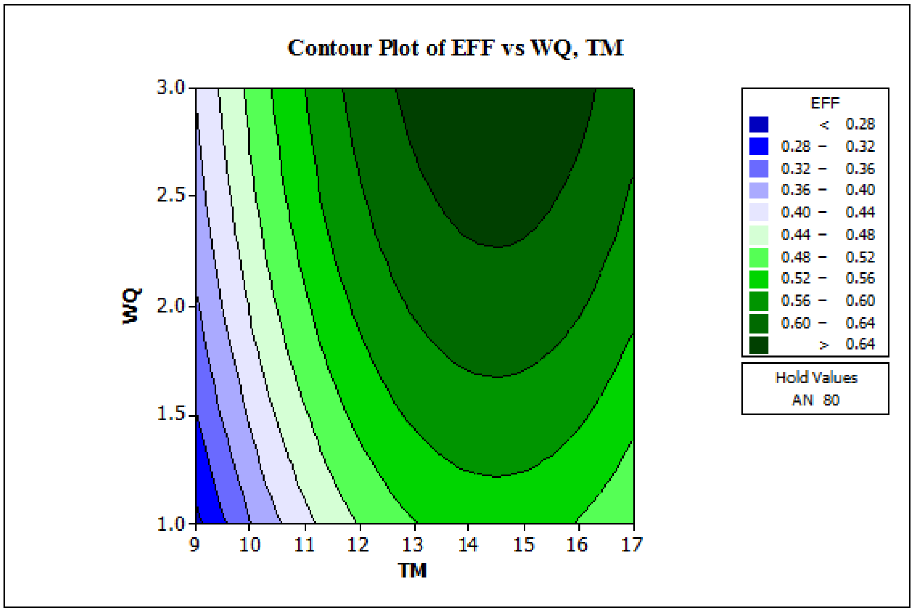


Figure 4: Surface plots for the Efficiency of the PSR(EFF) response



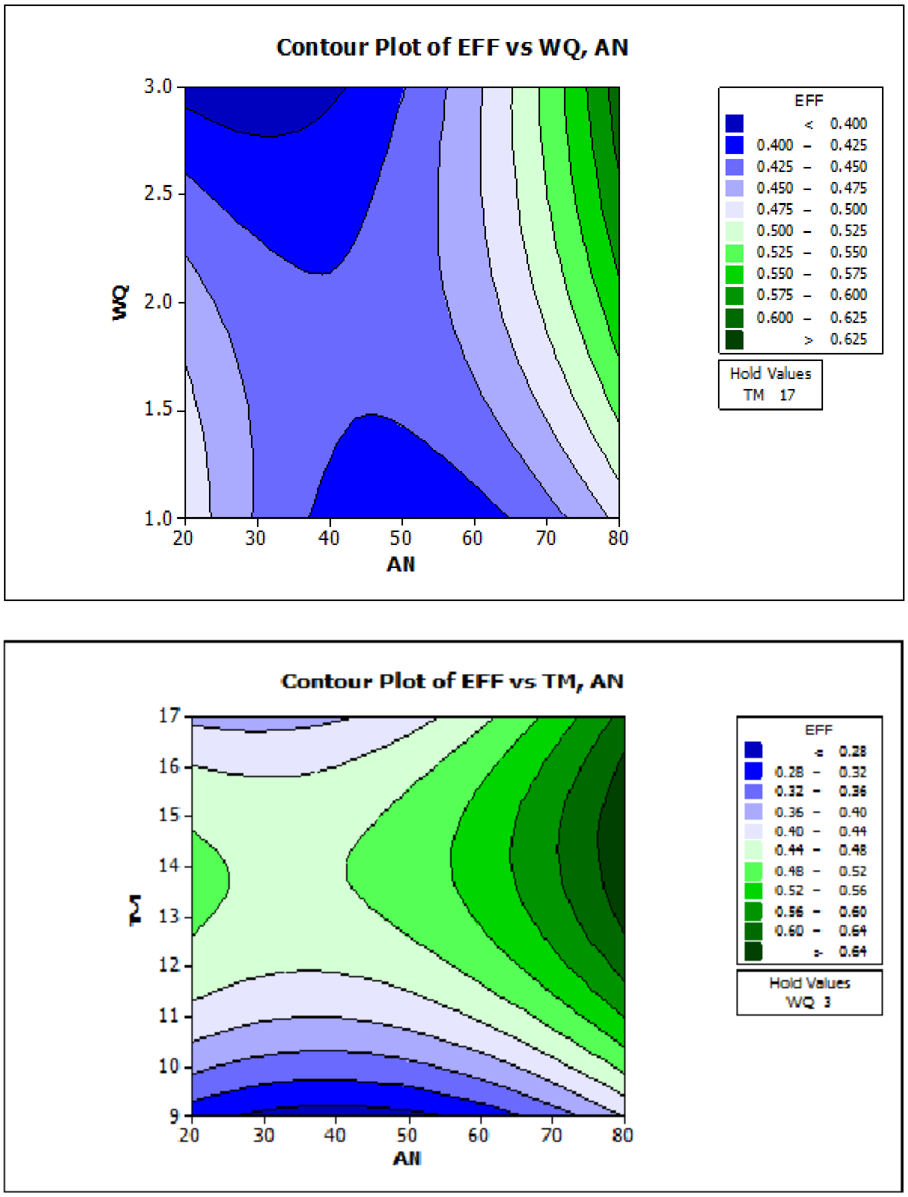


Figure 5: Contour plots for the Efficiency of the PSR(EFF) response

3.4 Sensitivity analysis

Sensitivity analysis, a method to identify critical parameters and rank them by their order of importance, is paramount in model validation where attempts are made to compare the calculated output to the measured data. This type of analysis can study which parameter must be most accurately measured, thus determining the input parameters exerting the most influence upon model outputs. Mathematically, sensitivity of a design objective function with respect to a design variable is the partial derivative of that function with respect to its variables. To obtain the sensitivity equation for both the response are differentiated with respect to input. The sensitivity equations (4) - (6) represent the sensitivity.

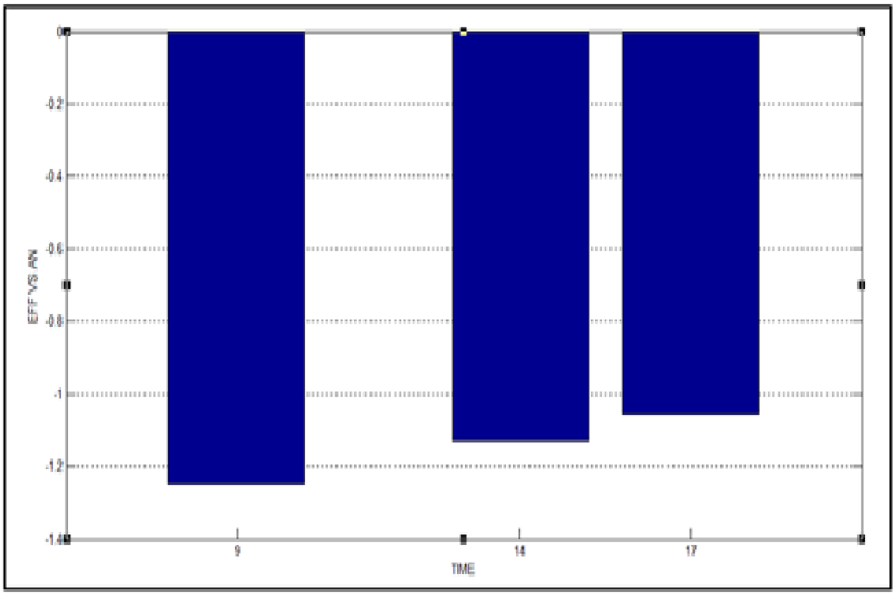
$$\frac{\delta EFF}{\delta AN} = -0.015013 - 2 * 8.7937E^{-05} * AN + 0.000242523 * TM + 0.00193111 * WQ \quad (4)$$

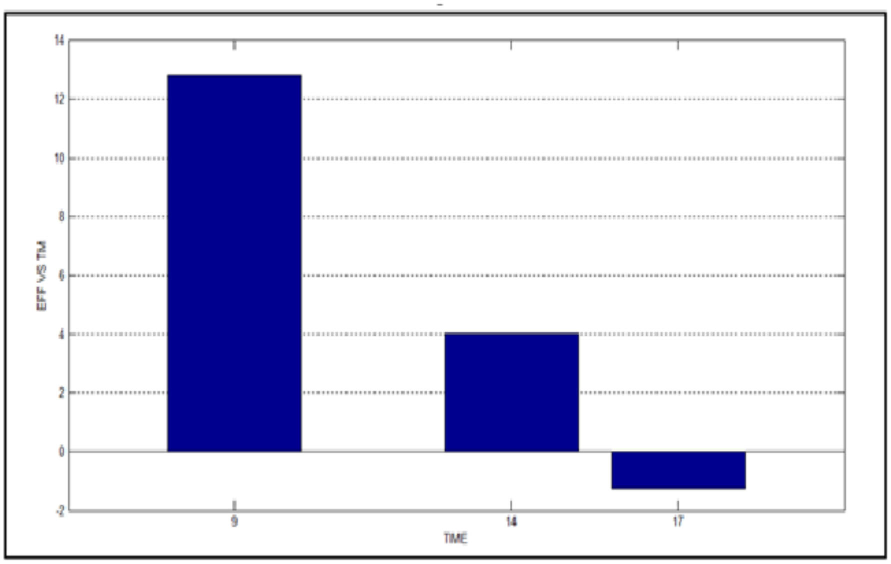
$$\frac{\delta EFF}{\delta TM} = 0238045 - 2 * 0.00888 * TM + 0.000242523 * AN \quad (5)$$

$$\frac{\delta EFF}{\delta WQ} = -0.0089744 - 2 * 0.0199586 * WQ + 0.00193111 * AN \quad (6)$$

Table 5: Sensitivity analysis of the response variables for WQ=2 liter

WQ	TM	AN	Sensitivity		
			$\frac{\delta EFF}{\delta AN}$	$\frac{\delta EFF}{\delta TM}$	$\frac{\delta EFF}{WQ}$
2	9	20	-1.24857	12.81	-8.4912
2	14	20	-1.12732	4.01	-8.4912
2	17	20	-1.05457	-1.27	-8.4912
2	9	50	-1.77615	20.085	-7.9119
2	14	50	-1.6549	11.285	-7.9119
2	17	50	-1.58215	6.005	-7.9119
2	9	80	-2.30373	27.36	-7.3326
2	14	80	-2.18248	18.56	-7.3326
2	17	80	-2.10973	13.28	-7.3326


0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
9
14
17
TIME


14
12
10
8
6
4
2
0
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EFF VS TM
9
14
17
TIME

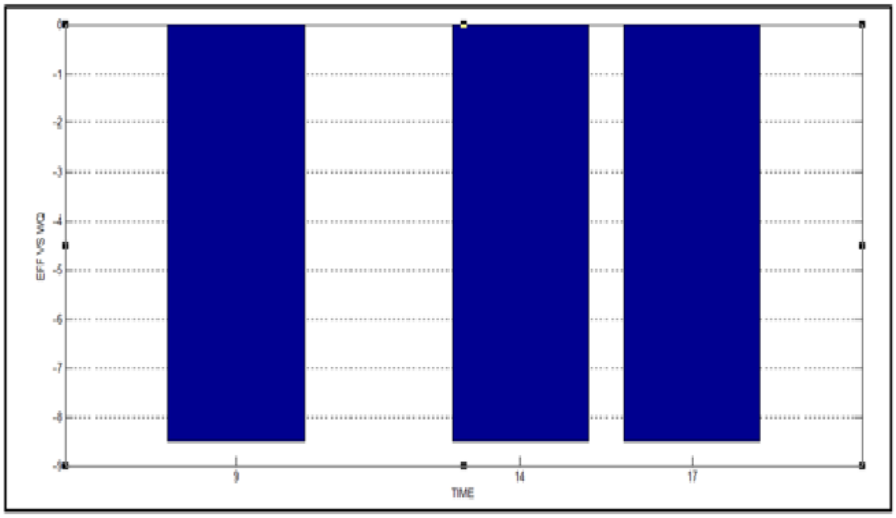

Figure 6: Sensitivity analysis of Efficiency result: (a) Tilting angle (AN);(b) Time (TM); (c) Water Quantity (WQ)

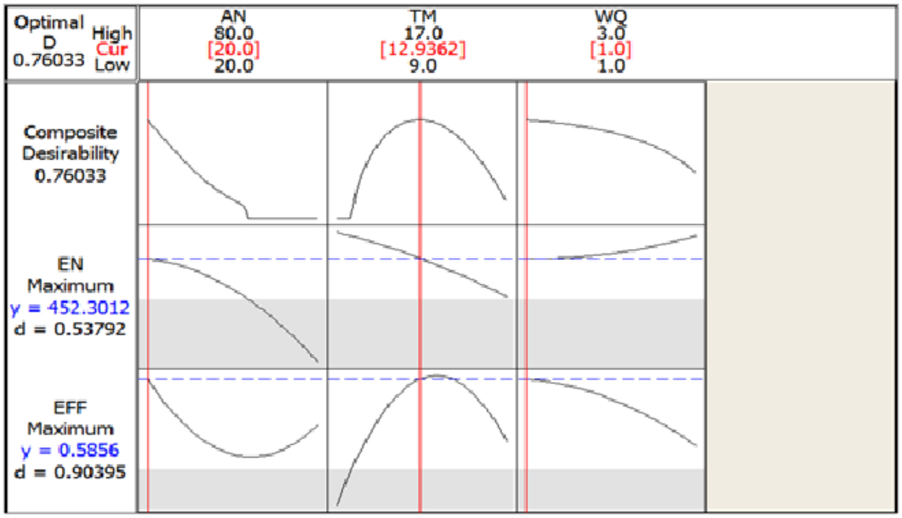

Figure 7: Composite desirability for the optimized result

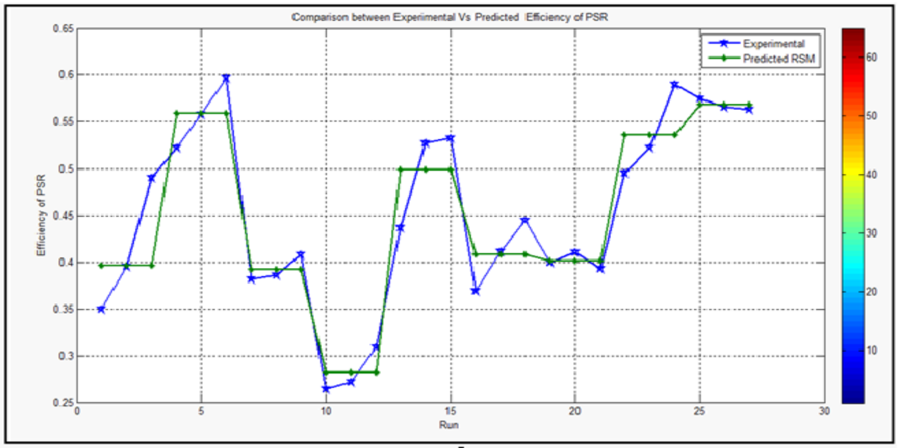

Figure 8: Comparison between experimental Vs Predicted efficiency of PSR

4 Conclusions

This paper has described the use of design of experiments (DOE) for conducting experiments. One models was developed for predicting the efficiency of the portable scheffler reflector using response surface methodology (RSM). From this investigation, the following important conclusions were derived.

- Angle is the factor that has greater influence on tensile efficiency, followed by water quantity and time.

- A maximum efficiency of 60% is exhibited by the PSR with the optimized parameters of 20 degree angle, one liter quantity and the 12.91 i.e. 1 O clock .

- The predictive RSM model is found to be capable of better predictions of efficiency and the results of the RSM model indicate it is much more robust and accurate in estimating the values of efficiency.

- Fig 8 shows that the actual efficiency is very closed with the RSM predicted efficiency. The correlation between the actual and the RSM predicted efficiency is 0.939603 which indicated that the system under investigation (PSR) is fully analyse by the use of response surface method.

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