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Optimization and Forecasting the Efficiency of Solar Water Heater by Mathematical Regression

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Abstract**:** ***The performance of the solar collector was experimentally studied under the different twist conditions namely helical twist, helical with left right twist and screw twist, L/D ratio (i.e., 0, 3 and 6) and time. Based on the standard relationship, efficiency of the collector was calculated for the different experimental combinations. Further, the significance of solar collector process parameters was identified by statistical analysis. Also the optimal solar collector process parameters to achieve the maximum the efficiency was identified and a mathematical regression was generated to forecast the efficiency of the solar collector.***

Keywords: Solar collector, efficiency, optimization.

I. INTRODUCTION

The present world is more focused on the energy conservation i.e., the effective utilization of energy. Particularly utilization of natural energy sources is highly promoted. Though plenty of natural energy sources are available in different forms, solar energy is the one which is found abundant compared with other sources with the advantages of inexhaustible, non-pollution, and renewable. Solar collector is an effective device which is used to transform the solar energy to heat energy through the working fluid, which has a direct and indirect applications in both the domestic and industries [1]. The effective utilization of the solar energy is highly relies on the performance of the solar water heater and hence the performance improvement of solar water heater is required [2]. Several methods were adopted to improve the performance of the solar water heater and some of the studies on the solar collector performance are detailed below. The solar flat plate collector efficiency was analysed by Alvarez et al. through the experimental and modelling and found the results are fit with the experimental results [2]. Balaji et al. investigated the performance of flat plate collector with the rod and tube heat enhancer and found the rod heat enhancer improved the performance of the collector [3]. Garcia et al. studied the performance of flat plate collector with the insertion of wires inside the tubes and obtained the optimal efficiency [4]. Murali and Mayilsamy studied performance of flat plate collector under the continuing and Batch wise discharging mode and found the open diffuser enhanced the performance in both conditions [5]. Upadhyay et al. studied flat plate collector performance with the tubes of internal grooves and found an improved efficiency for the grooved tubes [6]. The performance of the collector is also improved with the addition of micro and nano metal powders. He et al. investigated the performance of flat plate collector with Cu-H_2O nano-fluids under different fraction combinations and observed an improved performance with the addition of nano powders [7]. Youse et al. investigated the performance of flat plate collector with Al_2O_3-H_2O nano-fluids under different fractions and observed an improvement in the efficiency of 28% for 0.2 wt. % of nano alumina addition [8]. The identification of significant parameters and the optimization of solar collector process of parameters is mandate in order to improve the efficiency of the solar flat collector. Taguchi technique is one of the most wide using technique to optimize the process parameters in different fields [9–13]. Employing the Taguchi technique, the efficiency of the thermal solar collector was optimized by Jaya Suthahar and Jaisankar and identified the optimal parameters [14]. Owing to the literature, it is evident that an improvement of solar collector performance supports the energy utilization and directly results in the energy conservation. The present work focused on the optimization of solar collector process parameters by considering the L/D ratio, time and twist conditions.

II. EXPERIMENTATION

To study the performance of solar collector under a natural circulation condition, an experimental set up was indigenously built along with the necessary measuring devices at Star Lion College of Engineering and Technology, Thanjavur, Tamil Nadu, India as shown in the **Fig. 1**. The built set up comprises the 100 liters storage tank, collector, and riser tubes. Inside the riser tubes three different conditions of twist are introduced namely helical twist, helical with left right twist and screw twist as shown in **Table I**. The twists were made in three different L/D ratio namely 0, 3 and 6. By the all the above conditions, the experimentation was carried out through the day from 9:00 hours to 16:00 hours using water as working medium. The temperature of the working medium at the inlet and outlet condition, pressure drop were recorded at regular intervals. With the recorded values, the efficiency of the solar collector under each conditions were measured using the relationship as in equation (1) and it is shown in **Table II**.

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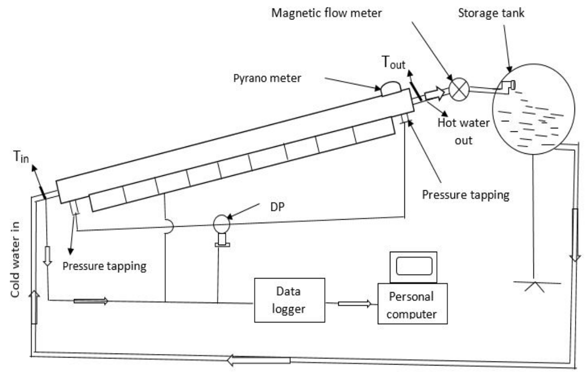


Fig. 1.Schematic layout of solar collector.

$$\eta = F_R(\tau\alpha) - F_R U_l \frac{T_{in} - T_a}{H_t} \qquad (1)$$

Table- I: Parameter and levels considered

L/D ratio	Time, hours	Twist condition
0	9	Helix (1)
3	13	HLR (2)
6	16	Screw (3)

Table- II: Experimental design with efficiency

S. No	L/D ratio	Time, hours	Twist condition	Efficiency
1	0	9	1	28.91
2	0	9	2	28.91
3	0	9	3	28.91
4	0	13	1	66.65
5	0	13	2	66.65
6	0	13	3	66.65
7	0	16	1	30.49
8	0	16	2	30.49
9	0	16	3	30.49
10	3	9	1	36.17
11	3	9	2	43.19
12	3	9	3	41.05
13	3	13	1	76.67
14	3	13	2	83.73
15	3	13	3	84.30
16	3	16	1	49.72
17	3	16	2	54.87
18	3	16	3	54.49
19	6	9	1	31.81
20	6	9	2	39.79
21	6	9	3	34.94
22	6	13	1	69.20
23	6	13	2	78.21
24	6	13	3	71.75
25	6	16	1	33.80
26	6	16	2	50.29
27	6	16	3	46.90

III. RESULT AND DISCUSSION

The aim is to compute the solar collector efficiency by considering the objective “Larger is better” as the efficiency needs to be maximized.

A. Analysis of parameters

The influence of parameters on the efficiency of solar collector is need to be analysed as it has significant influence on the performance of the solar collector. The analysis performed on the collected data exhibits the parameter influence as shown in Table III and IV. Table III displays the response table with the values of delta 6.57 for Time, 3.12 for L/D ratio and 1.07 for twist condition. This shows that the time factor has a dominant influence on the solar collector efficiency compared with other. L/D ratio is the second dominant factor over the efficiency followed by twist condition. Table IV displays the variance analysis for the efficiency of solar collector with 97.26 regression coefficient which shows that the all the three parameters have a significance on the efficiency with the probability value of <0.05. When considering the percentage probability of the parameters, 82.71% is attained for Time, and 12.82 for L/D ratio. This evident the time has dominant effect on the performance of solar collector.

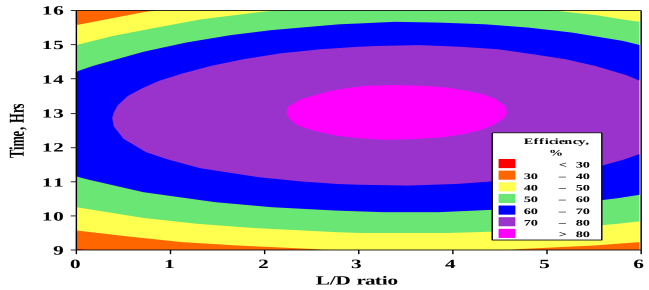
Table- III: Response table (Larger is better)

Level	L/D ratio	Time, hours	Twist condition
1	31.79	30.75	32.84
2	34.92	37.32	33.91
3	33.64	32.28	33.59
Delta	3.12	6.57	1.07
Rank	2	1	3

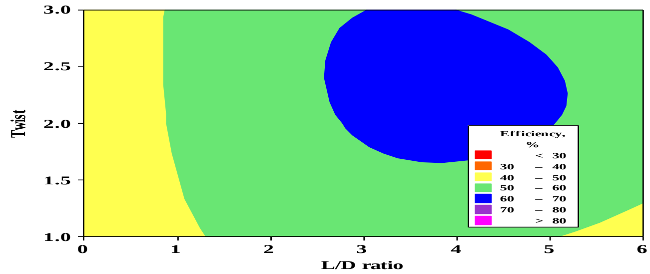
Table- IV: Analysis of variance for efficiency

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P%
L/D ratio	2	1187.2	1187.2	593.6	46.85	0.000	12.82
Time, Hrs	2	7661.7	7661.7	3830.8	302.34	0.000	82.71
Twist	2	161.3	161.3	80.6	6.36	0.007	1.74
Error	20	253.4	253.4	12.7			2.74
Total	26	9263.6					100

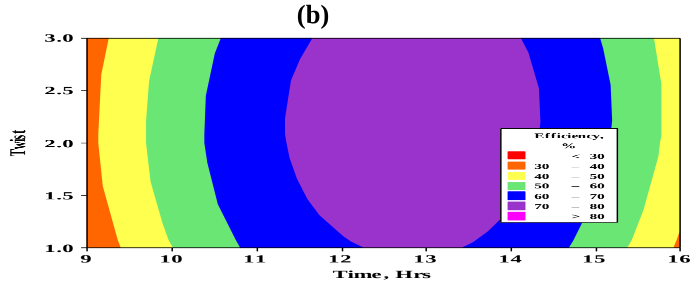
S = 3.55961   R-Sq = 97.26%   R-Sq(adj) = 96.44%



(a)



(b)



(c)

Fig. 2.Contour plot for efficiency (a) L/D ratio with time (b) L/D ratio with twist (c) Time with twist

The contour plot for the efficiency of solar collector is plotted with the parameters as shown in Fig. 2. Fig .2(a) is plotted between L/D ratio and time which shows highest efficiency of greater than 80% at 13:00 hours' time with the medium L/D ratio. Also, the further reduction or increase in time and L/D ratio displays a declined efficiency. Fig .2(b) is plotted between L/D ratio and twist which shows highest efficiency of greater than 60% at medium L/D ratio with twist condition of helix left right twist and screw twist condition. Fig .2(c) is plotted between Time with twist which shows highest efficiency of greater than 70% at13:00 hours' time with all the twist conditions. The contour plot also clearly depicts the dominance of time and L/D ratio on the efficiency of solar collector.

B. Optimal solution

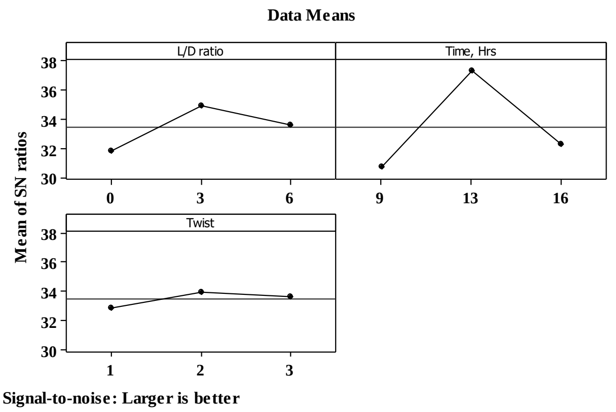


Fig. 3.Main effect plot for efficiency

Fig.3 displays the main effect plot for the efficiency of solar collector, with the optimal parameter of L/D ratio as 3, Time as 13:00 hours and Twist condition as Helix with left right twisted condition. The reason is at the time of 13:00 hours the solar intensity is found to be high which has a direct influence on the temperature of working medium. The twist condition of Helix with left right twist indigenously generate an alternate swirl in the working fluid {i.e., initially it swirls on the clockwise direction and then it swirls in anticlockwise direction), which helps the conduction mode of heat transfer between the working fluid and the riser tube. When the L/D ratio is increased it leads to the increased length of twist which may not supports the effective heat transfer as it reduces the swirl of working fluid, therefore the medium L/D ratio is attained as the optimal level.

C. Efficiency model

To predict the efficiency of solar collector under the different parametric condition, a mathematical regression is generated with 97.98 % of R-Sq as shown in equation (2).

$$\begin{aligned}\text{Efficiency, \%} = & -400.644 + 6.45008 \text{ L/D ratio} \\ & + 72.2524 \text{ Time, Hrs} \\ & + 12.9707 \text{ Twist} \\ & - 1.31821 \text{ L/D ratio} * \text{L/D ratio} \\ & + 0.14767 \text{ L/D ratio} * \text{Time, Hrs} \\ & + 0.521608 \text{ L/D ratio} * \text{Twist} \\ & - 2.88293 \text{ Time, Hrs} * \text{Time, Hrs} \\ & + 0.227169 \text{ Time, Hrs} * \text{Twist} \\ & - 3.85246 \text{ Twist} * \text{Twist}\end{aligned} \quad (2)$$

D. Validation

The validation of the developed mathematical regression was done by predicting the efficiency of the solar collector and the same is compared with the experimental efficiency for all the experiments as shown in Table V. The comparison of predicted efficiency with the experimental efficiency shows an accuracy of 94.76 % and error of 5.24%.

Table- V: Validation of efficiency

S.No	Experimental Efficiency	Predicted Efficiency	Error, %
1	28.91	27.27	5.68
2	28.91	30.73	6.28
3	28.91	26.48	8.41
4	66.65	63.49	4.74
5	66.65	67.86	1.82
6	66.65	64.52	3.19
7	30.49	30.12	1.21
8	30.49	35.17	15.35
9	30.49	32.51	6.63
10	36.17	40.31	11.44
11	43.19	45.33	4.96
12	41.05	42.65	3.90
13	76.67	78.30	2.13
14	83.73	84.24	0.60
15	84.30	82.46	2.18
16	49.72	46.26	6.97
17	54.87	52.87	3.64
18	54.49	51.78	4.99
19	31.81	29.62	6.89
20	39.79	36.21	9.01
21	34.94	35.09	0.43
22	69.20	69.39	0.27
23	78.21	76.88	1.70
24	71.75	76.67	6.86
25	33.80	38.67	14.40
26	50.29	46.85	6.84
27	46.90	47.32	0.89
Overall Error, %			05.24
Accuracy, %			94.76

IV. CONCLUSION

Indigenous solar flat collector setup was developed and the performance of the collector was studied at different time, twist conditions namely helical twist, helical with left right twist and screw twist, and L/D ratio. The solar collector efficiency was calculated and with the results optimization was performed by means of Taguchi technique. The analysis yield the optimal parameter of L/D ratio as 3, Time as 13:00 hours and Twist condition as Helix with left right twisted condition. Though the L/D ratio and Twist condition showed a significance, Time has a dominant influence on the solar collector efficiency. The validation of the mathematical regression with the experimental efficiency showed a good correlation with accuracy of 94.76%.

APPENDIX

DF - Degrees of freedom
Seq SS - Sequential sums of squares
Adj SS - Adjusted sums of squares
Adj MS - Adjusted mean squares
P - Probability
P% - Probability percentage

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