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Multi-objective optimization of flat-plate solar collectors using the Taguchi method and Grey relational analysis

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ABSTRACT

Flat-plate solar collectors are widely used in solar water heating systems, but their thermal performance depends strongly on design and processing parameters. This study presents a multi-objective optimization of a flat-plate solar collector using the Taguchi method combined with Grey relational analysis. Six control factors—collector tube material, absorber plate material, number of collector tubes, tube diameter, absorption film type, and insulation thickness—along with two noise factors were investigated using an L18 orthogonal array to minimize experimental effort. The efficiency coefficient and heat dissipation factor were selected as performance characteristics and evaluated using larger-the-better and smaller-the-better criteria, respectively. Signal-to-noise ratios and ANOVA were employed to assess robustness and parameter significance. Results show that the number of collector tubes is the most influential factor, followed by absorber plate material and absorption film type. The optimized parameter combination significantly improved collector performance, and confirmation experiments validated the proposed optimization model...

Keywords: *Flat-plate solar collector; Taguchi method; Grey relational analysis; Multi-objective optimization; Thermal performance; Solar water heating system*

1. INTRODUCTION

A key part of the solar water heating system is the flat-plate collector. It is made up of an outer frame, a surface cover, a thermal insulating layer, and an endothermic plate. The primary

Fig. 1 depicts the flat-plate collector's structure. The flat-plate collector's primary operating principle [1-3] is that solar radiation energy enters the collector through its surface cover and, once coming into contact with the endothermic plate's absorption film, transforms into thermal energy. The endothermic plate uses thermal conduction to transfer the absorbed heat energy to the collector tube's outer wall. The scope is covered by solar radiation energy from the UV to infrared radiation having wavelengths between 0.2 and 4 mm. Thermal convection transfers the high-temperature energy to the collector tube wall to the working media that passes through the tube, heating it. The endothermic plate was found to have insulating material on its side face and bottom to minimize heat loss, as well as a surface cover on top to lessen heat loss from radiation and convection.

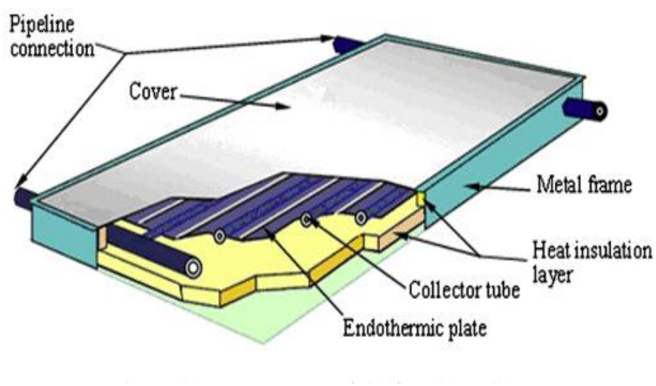

Fig. The main structure of the flat-plate collector

Based on the energy balance equation, Hottel and Wertz [4] carried out theoretical investigations and evaluations of the flat-plate collector in 1942. Garg and Agarwal [5] investigated the connection between the working media flow rate inside the collector tube and the flat-plate collector's thermal collection efficiency through simulation. The efficiency is higher when the working liquid flows at a high rate inside the collector tube, according to the results.

Naharand Gupta [6] carried out an experimental comparison on the impact of variations in the distance between the flat-plate collector's glass surface cover and endothermic plate on thermal collection efficiency, in order to identify the ideal distance. Yeh et al. [7] examined the solar flat-plate collector efficiency using both theoretical and experimental research, as well as the impact of an increasing number of collector tubes on the flat-plate collector efficiency while the flat-plate collector's area is unchanged. Eisenmann et al. [8] conducted an experiment based on the correlation between the endothermic plate efficiency and different processing parameters, and calculated the correlation between the economic surface and endothermic plate material. The relationship between the solar flat-plate collector's performance and processing parameters was further examined by Farahat et al. [9], who postulated that the solar flat-plate collector's endothermic plate area, size, collector tube diameter, mass flow rate, inlet liquid temperature, and outlet liquid temperature are all variable parameters.

The majority of the aforementioned research did not address the parameter combination; instead, they focused solely on the link between the flat plate collector's performance and processing parameters. For the flat-plate collector's optimal overall performance. The relationship between the flat-plate collector's performance and processing parameters was therefore further optimized in this investigation.

In order to optimize the processing parameters, this study ran an experiment using parameter allocation. Typically, empirical guidelines or trial and error are used to determine experimental parameters approach, which is expensive and time-consuming. To get the processing parameter optimization for the synthesis of the CIGS (copper indium gallium (di) selenide) thin film solar cell, Liu et al. [10] designed an experiment based on the Taguchi method and the L18 orthogonal array. In order to maximize the electrical and optical characteristics of the ITO (indium tin oxide) thin-film solar cell, Jun et al. [11] created an experiment based on the Taguchi technique and ultimately determined the ideal processing settings.

Nevertheless, only one quality feature may be optimized using the Taguchi experimental design method. When there are numerous quality characteristics, the multiple quality analysis procedure is necessary. Based on the Taguchi method and grey relational analysis, Chen et al. [12] transformed a number of quality attributes into GRG (grey relational grade) and arranged different quality attributes based on their answers in order to choose the best set of processing parameters. Tarng et al. [13] used the Taguchi technique and grey relational analysis to examine several arc welding quality characteristic issues. The GRG The best combination of processing parameters for several quality attributes was determined by calculating the SN ratio (signal-to-noise ratio) of the experimental data acquired using the Taguchi method. In order to identify the ideal numerous quality parameters and enhance the output of the thin Cr (chromium) film, Chiang and Hsieh [14] experimented with the colour filter process using the Taguchi technique and grey relational analysis. In conventional experimental design, a full-factorial orthogonal array must account for all possible combinations of factor levels. For the system analyzed in this work, eight parameters are involved; comprising one factor with two levels and seven factors with three levels each experimental runs. Conducting this many trials is labor-intensive and significantly increases the total experimentation time, making the full-factorial approach unsuitable for practical implementation. However, in order to retain the robustness of the trials, only eighteen experiments were carried out utilizing the L18 orthogonal array in this work, which used the Taguchi approach for experimental planning. The efficiency coefficient and heat dissipation factor are the two quality characteristics of the flat-plate collector utilized in this investigation. In order to achieve process optimization, a number of quality attributes were combined using the Taguchi technique and grey relational analysis to find the best combination of processing parameter levels.

2. Research methods

2.1. **The Taguchi technique**: In order to get the most information with the fewest experiments, the Taguchi approach is used to construct experiments based on orthogonal arrays. It may also assess the experimental data using the SN ratio. The efficiency coefficient and heat dissipation factor are the flat-plate collector's quality characteristics that are examined in this study. A lower heat dispersion coefficient and a greater efficiency coefficient are ideal for flat-plate collectors. Consequently, the quality attributes of the efficiency coefficient and heat dispersion factor are defined as follows: the former is characterized by a bigger value being preferable, while the latter is characterized by a smaller value being preferable [10, 11].

$$SN = -10log_{10} + \frac{1}{m}\sum_{i=1}^{m}\frac{1}{(x^2{}_i)}$$

---------------[1]

$$SN = -10log_{10} + \frac{1}{m}\sum_{i=1}^{m}(x^2{}_i)$$
----------------[2]

Where, x_i is a quality measurement; and **m** is the total of the measurements. Following the preparation of the experiment, a response graph is produced and the experiment is carried out to collect the experimental data produced by the combination of different orthogonal parameters in the orthogonal array. The SN ratio is first obtained by calculating the experimental data; the technique of calculation is contingent upon the desired quality criteria. After calculating the average response value ($\overline{f_i}$) for each factor level, the major effect value (Δf)) for each factor level is determined. For each factor's effect analysis, these data are plotted onto a response graph. In comparison to other factors, a factor's influence on the system increases with its main effect value (Δf). Conversely, a factor's quality enhancement effect is not significant if its main effect value Δf) is smaller than that of other factors. The computations can be written as follows.

$$\bar{f}\,\mathrm{i} = \frac{1}{n}\sum_{j=1}^{n}\eta_{ij}$$
------------------ [3]

(Δf)= max($\overline{f_1}, \overline{f_2}, \overline{f_3}, \ldots\ldots, \overline{f_d}$**) – min ((** $\overline{f_1}, \overline{f_2}, \overline{f_3}, \ldots\ldots, \overline{f_d}$**)** ---------- [4]

2.2. **Analysis of variance, or ANOVA**

The Taguchi experimental plan's SN ratio is used to assess the quality characteristics; however each factor's impact on the flat-plate collector's quality features is not obtainable from the SN ratio. To determine the impact of different factors, the ANOVA assesses the experimental errors and test of significance. The ANOVA's procedure and formula are listed below [15].

2.**2.1.** ν **(Freedom degree)**

Each factor's degree of freedom, or DOF, is equal to its level number minus 1. The number of experiments less one equals the total DOF. The value of the overall DOF less the sum of the DOF of each factor is the error of the DOF (νe).

2.2.2. ***CF*** **(correction factor)**

$$CF = \frac{(\sum_j^m = 1\eta_i)^2}{m}$$ ---------------------[5]

Where η the SN ratio of experimental observations and **m** is is the number of the experiments.

2.2.3. *SS* **(Sum of square)**

$$SS = \frac{\sum_{i=1}^{m/n}(\sum_j^n = 1\eta_{ij})^2}{n} - \mathrm{CF}$$ **---------------[6]**

Where, **n** is the number of each level of the factor.

2.2.4. ***TSS*** **(total sum of square)**

$$\mathrm{TSS} = \sum_{j=1}^{m}(\eta_j)^2 - \mathrm{CF}$$ **--------------[7]**

2.2.5. ***SSe*** **(error sum of square)**

$$\mathrm{SSe} = \mathrm{TSS} - \sum_{k=1}^{q} SSq$$ **-------------- [8]**

Where **q** is the factor's number. There is no DOF for error while utilizing saturated orthogonal array. To put it another way, the SSes is 0 and there is no error term. In certain trials, a small number of factors may be significant, or all the factors may be highly significant. As a result, the pooling technique must be used to estimate error; in an orthogonal array experiment, pooling half of the degrees of freedom is typically advised.

2.2.6. V (variance)

It is the SS divided by the DOF

$$\boldsymbol{V} = \frac{\boldsymbol{SS}}{\boldsymbol{v}} \quad \text{------------------- [9]}$$

V_e (error mean sum of square)can be expressed as,

$$\boldsymbol{V_e} = \frac{\boldsymbol{SS_e}}{\boldsymbol{v_e}} \quad \text{------------------[10]}$$

2.2.7. F (F-ratio) It is the variance of each factor divided by the error variance.

$$\boldsymbol{F} = \frac{\mathbf{V}}{\mathbf{V_e}} \quad \text{------------------ [11]}$$

2.3. Confidence intervals or CI

Confirming the mathematical model's reasonableness based on the experimental results is the goal of the confirmatory test acquired using the orthogonal array. The addition model and the set value of the best suitable factor level are used to anticipate the SN ratio under ideal circumstances. The CI equation is [15].

$$\mathrm{CI} = \sqrt{f_{\alpha;}\,1, \upsilon_2 \times \mathrm{V_e} \times \left(\frac{1}{m_{eff}} + \frac{1}{r}\right)} \quad \text{---------------------[12]}$$

Where $f_{\alpha;}\,1, \upsilon_2$ is the tabulated F-ratio, α is the risk with confidence level equals to 1, -α, υ_2 is the number of degrees of freedom for the numerator associated with the pooled error variance, V_e is the pooled error variance, and r is the sample size, m_{eff} is the effective number of experimental observations and calculated as,

$$m_{eff} = \frac{\text{total number of experiments}}{\text{sum of degrees of freedom used in estimate of mean}} \quad \text{-------------[13]}$$

The $\hat{\eta}$ is the SN ratio estimation with the optimum factor levels, μ is the processing parameter estimated, and their expressions are regarded as,

$$\hat{\eta} = T + \sum_{i=1}^{p} \overline{F_i} - T \quad \text{------------- [14]}$$

$$\hat{\eta} - CI \leq \mp \mu \leq \hat{\eta} + CI \quad \text{----------------[15]}$$

Where, p is the number of significant processing parameters is the total average of the SN ratios in the experiment, and f_i is the mean response value of the ith level of the significant processing parameters.

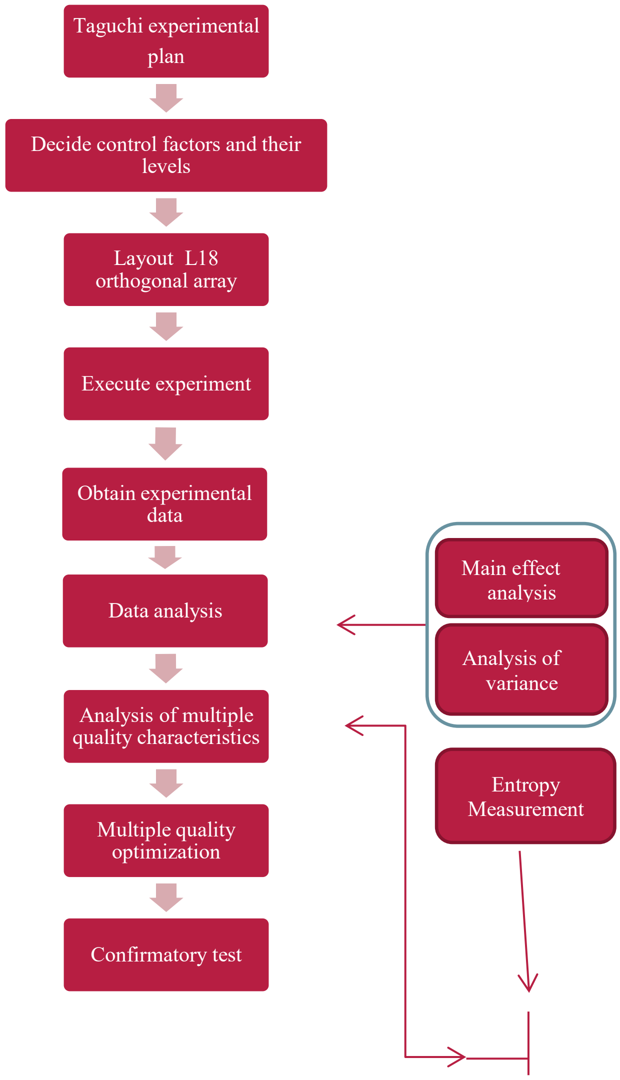

Fig.2. Flowchart of the methodology.

Table 1. Controlling factors of the flat-plate collector and their levels.

Controlling factor	**Level Value**		
	1.	2	3
A. Collector tube material	(A1) Copper	(A2) Stainless steel	
B. Endothermic plate material	(B1) Aluminum	(B2) Copper	(B3) Stainless Steel
C. Number of collector tubes (piece)	(C1) 9	(C2) 12	(C3) 15
D. Collector tube diameter (1/800)	D1) 4	(D2) 5	(D3) 6
E. Absorption film type	(E1) Tinox	(E2) Vacuum sputtering	(E3) Spray painting
F. Thickness of the bottom heat insulating material (cm)	(F1) 2.6	(F2) 3.9	(F3) 5.2

Table 2 Interference factors of the flat-plate collector and their levels.

Controlling factor	**Level Value**		
	1.	2	3
p. Illumination intensity (W/m2)	(p1) 900	(p2) 1000	(p3) 1100
q. Temperature (_C)	(q1) 20	(q2) 30	(q3) 4 0

Table. 3 Allocation table of experimental factors of the flat-plate collector

Sr.No	**A**	**B**	**C**	**D**	**E**	**F**
	1	1	1	1	1	1
	1	1	1	1	2	2
	1	1	1	1	3	3
	1	2	2	2	1	1
	1	2	2	2	2	2
	1	2	2	2	3	3
	1	3	3	3	1	1
	1	3	3	3	2	2
	1	3	3	3	3	3
	2	1	2	3	1	2
	2	1	2	3	2	3
	2	1	2	3	3	1
	2	2	3	1	1	2
	2	2	3	1	2	3
	2	2	3	1	3	1
	2	3	1	2	1	2
	2	3	1	2	2	3
	2	3	1	2	3	1
	3	1	3	2	1	3
	3	1	3	2	2	1
	3	1	3	2	3	2
	3	2	1	3	1	3
	3	2	1	3	2	1
	3	2	1	3	3	2
	3	3	2	1	1	3
	3	3	2	1	2	1

Table 4. Test result of the efficiency coefficient

Sr.No	Eff	SNRA1
	0.7688	-2.28373
	0.7456	-2.54988
	0.7430	-2.58022
	0.7520	-2.47564
	0.7334	-2.69318
	0.7655	-2.32110
	0.5866	-4.63316
	0.6238	-4.09909
	0.7233	-2.81363
	0.6855	-3.27985
	0.7589	-2.39631
	0.7977	-1.96321
	0.8244	-1.67724
	0.6433	-3.83173
	0.6654	-3.53834
	0.7234	-2.81243
	0.7456	-2.54988
	0.6677	-3.50837
	0.5678	-4.91609
	0.6211	-4.13677
	0.7566	-2.42267
	0.7822	-2.13364
	0.8100	-1.83030
	0.7234	-2.81243
	0.6500	-3.74173
	0.7900	-2.04746

However, since the significance of each factor on the system may vary, according to the different weight of each factor, the GRG is also defined as,

$$\boldsymbol{\gamma_{0,j} = \gamma(x_j, x_i) = \frac{1}{m}\sum_{l=1}^{m} \beta_l \gamma_{0,j}(l)}$$ -------------[24]

Where, β_l is the normal weight of factor l, $\sum_{l=1}^{m}$ & β_l =1, different weights can be given to different factors based on their Influences on the system.

3. Results and Discussion

3.1 Signal-to-Noise Ratio Analysis for Efficiency Coefficient

The experimental results for the efficiency coefficient and the corresponding signal-to-noise (SN) ratios, calculated using the *larger-the-better* criterion, are presented in Table 4. The SN ratio transforms the raw experimental data into a measure of robustness by accounting for variability and noise factors.

A higher SN ratio indicates superior performance and stability of the flat-plate collector under varying experimental conditions. The SN ratios obtained in this study range from −1.677 to −4.916, reflecting the sensitivity of collector efficiency to changes in processing parameters.

The response graph for the SN ratios of the efficiency coefficient is shown in Fig. 3. From the response graph, the effect of each controlling factor on the efficiency coefficient can be visually interpreted based on the slope and variation of SN ratios across different levels.

It is observed that:

Factor C (number of collector tubes) shows the largest variation in SN ratio, indicating a dominant influence on efficiency.

Factors B (endothermic plate material), D (collector tube diameter), and E (absorption film type) show moderate influence.

Factors A (collector tube material) and F (insulation thickness) exhibit relatively smaller variations, suggesting a weaker effect on efficiency within the tested range.

The optimal levels for maximizing the efficiency coefficient, based on the highest SN ratios, are obtained by selecting the level corresponding to the maximum average SN ratio for each factor.

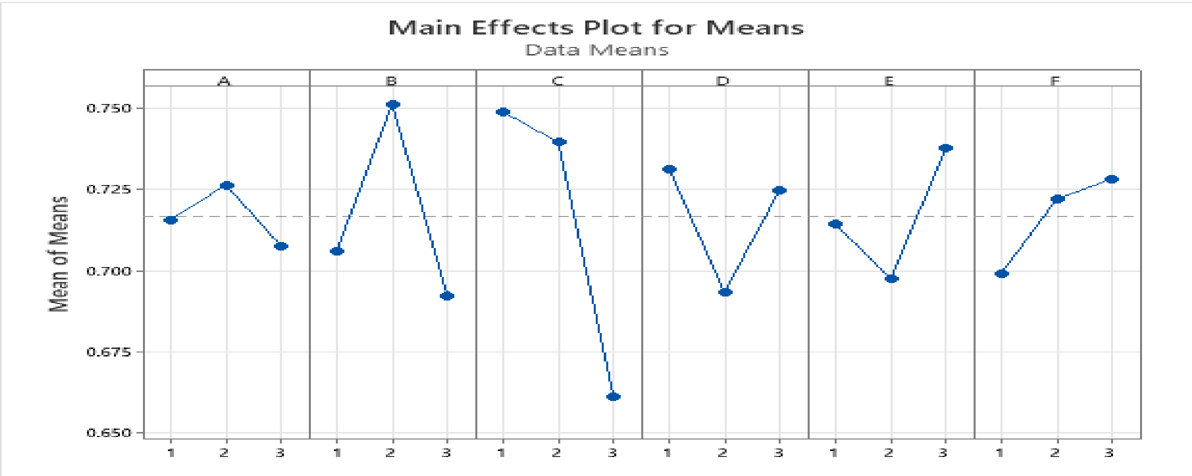

Fig. 3. Response graph for efficiency coefficient.

3.2 Analysis of Variance (ANOVA)

To quantitatively evaluate the statistical significance of each processing parameter on the efficiency coefficient, ANOVA was performed on the SN ratios. The results are summarised in Table 5.

From the ANOVA results:

Factor C (number of collector tubes) has the highest F-value (7.45) and a p-value of 0.006, indicating that it is statistically significant at a 95% confidence level.

Factor B (endothermic plate material) shows a moderate influence with a p-value of 0.094, suggesting partial significance.

Other factors (A, D, E, and F) have p-values greater than 0.1, indicating that their effects on efficiency are statistically less significant within the experimental domain.

The dominance of the number of collector tubes can be attributed to the increased heat transfer area and enhanced convective heat exchange between the absorber plate and the working fluid as the number of tubes increases. This result is consistent with previous studies reported in the literature.

The residual error contribution indicates that the selected factors and levels adequately capture the major sources of variability in the system.

Table 5. Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.3013	0.3013	0.1507	0.33	0.726
B	2	2.5829	2.5829	1.2914	2.81	0.094
C	2	6.8471	6.8471	3.4235	7.45	0.006

D	2	1.1219	1.1219	0.5609	1.22	0.325
E	2	1.1040	1.1040	0.5520	1.20	0.330
F	2	0.8073	0.8073	0.4036	0.88	0.437
Residual Error	14	6.4336	6.4336	0.4595		
Total	26	19.1981				

The flowchart of the methodology is shown in Fig. 2.

3.5 Confirmation Test and Model Adequacy

A confirmation experiment was conducted using the optimal parameter levels identified through the Taguchi–Grey relational approach. The predicted SN ratio and GRG values were calculated using the additive model and compared with the experimentally obtained results. The experimental results were found to lie within the calculated confidence interval, confirming the adequacy and reliability of the proposed optimisation model. The improvement in overall performance validates the effectiveness of combining the Taguchi method with Grey Relational Analysis for multi-response optimisation of flat-plate solar collectors.

3.6 Discussion

The results clearly demonstrate that system-level optimisation, rather than single-parameter analysis, is essential for improving flat-plate collector performance. Among all the factors studied, the number of collector tubes emerges as the most influential parameter due to its direct impact on heat transfer surface area and fluid–solid interaction. The application of the Taguchi method significantly reduced the number of required experiments while maintaining statistical robustness. The integration of Grey Relational Analysis further enabled simultaneous optimisation of conflicting quality characteristics, which is not possible using conventional Taguchi analysis alone. Overall, the proposed methodology provides a systematic, efficient, and reliable framework for optimising flat-plate collector design parameters and can be extended to other solar thermal systems.

5. Conclusion

In this study, the performance of a flat-plate solar collector was systematically optimised using a combined Taguchi method and Grey Relational Analysis approach. Multiple design and processing parameters affecting collector performance were investigated simultaneously, with the efficiency coefficient and heat dissipation factor selected as the key quality characteristics. The use of an L18 orthogonal array significantly reduced the number of experimental trials while maintaining statistical reliability.

Signal-to-noise ratio analysis and analysis of variance revealed that the number of collector tubes is the most influential parameter affecting collector performance, owing to its direct impact on heat transfer area and fluid–solid interaction. The endothermic plate material and absorption film type were also found to have notable effects, whereas collector tube material, tube diameter, and insulation thickness showed comparatively smaller influences within the investigated range.

By integrating multiple quality characteristics into a single grey relational grade, Grey Relational Analysis enabled effective multi-objective optimization that is not achievable using the Taguchi method alone. The optimal parameter combination identified through the Taguchi–GRA approach resulted in improved overall collector performance, and the confirmation experiment demonstrated good agreement with the predicted results, validating the robustness of the proposed optimization model.

The results confirm that system-level optimization is essential for enhancing flat-plate collector performance and that the combined Taguchi–Grey relational method provides an efficient, reliable, and practical framework for multi-response optimization. The methodology presented in this study can be readily extended to the design and optimization of other solar thermal and energy conversion systems.

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