



OPEN Performance optimization for solar photovoltaic thermal system with spiral rectangular absorber using Taguchi method

Jitendra Satpute^{1✉}, Srinidhi Campli², Dhinesh Balasubramanian^{3✉}, P. V. Elumalai^{4,5,6}, Raju Panchal², Yasser Fouad⁷, Manzoore Elahi M. Soudagar^{8,9,12}, J. Laxmi Prasad¹⁰ & Mesay Dejene Altaye^{11✉}

Solar collector systems efficiently transform sunlight into energy that may be used to meet various needs. This research aimed to use the Taguchi method to determine the ideal operating parameters for a solar thermal collector with a rectangular spiral absorber. Controllable parameters including mass flow rate, solar radiation, and absorber design were manipulated during the energy recovery process, and features like PV temperature and outlet water temperature were used to assess the system's effectiveness. The findings indicate that certain criteria significantly affect response indicators. The observed percentage contribution of absorber design, solar radiation, and the mass flow rate was 69.19%, 27.99%, and 2.83% in PV surface temperature. In comparison, the individual percentage contributions were 73.63%, 13.51%, and 10.57% for absorber design, solar radiation and mass flow rate for water output temperatures. The present model's R^2 values for PV and outlet water temperatures are 97.24% and 99.67%, respectively. The Predictive regression model was found in fine harmony and the maximum percentage error is limited to 0.68%. The maximum analytical electrical efficiency was observed with a spiral rectangular absorber of 14.57% at the lowest mass flow rate of 0.04 kg/s at the lowest radiation level of 600 W/m². In comparison, maximum analytical thermal efficiency was observed with a spiral rectangular thermal absorber of 63.56% at the highest flow rate of 0.06 kg/s and the highest solar radiation level of 1000 W/m². The analytical and experiment findings were in better agreement in this study, with the highest relative error of 7.52%. According to the study's findings, the rectangular absorber-based PVT system is at its best at a higher mass flow rate to lower PV temperature and boost thermal energy recovery via water. The present research work can be extended for exergy, environmental, and economic feasibility analysis.

Keywords Spiral rectangular absorber, Optimization, S/N ratio, Photovoltaic thermal system, Thermal energy recovery, Energy efficiency

During 2020, the amount of solar power generated was 724.09 terawatt-hours, which is roughly a 10.30% share of total renewable energy generation¹. Solar thermal collectors capture solar radiation and transform it into heat, while solar photovoltaic collectors convert solar radiation into electrical power. Because solar PV technology generates electricity directly without the need for moving parts, it has grown in popularity. According to the

¹Suman Ramesh Tulsiani Technical Campus Kamshet, Pune 410405, India. ²JSPM Rajarshi Shahu College Of Engineering, Pune, India. ³Department of Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi, Tamil Nadu, India. ⁴Department of Mechanical Engineering, Aditya University, Surampalem, India. ⁵Research Fellow, Faculty of Engineering, Shinawatra University, Toei, Thailand. ⁶Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, Tamil Nadu 602105, India. ⁷Department of Applied Mechanical Engineering, College of Applied Engineering, Muzahimiyah Branch, King Saud University, Riyadh, Saudi Arabia. ⁸Centre of Research Impact and Outcome, Chitkara University, Rajpura 140417, Punjab, India. ⁹Division of Research and Development, Lovely Professional University, Phagwara 144411, Punjab, India. ¹⁰Department of Mechanical Engineering, MLR Institute of Technology, Hyderabad, Telangana, India. ¹¹Department of Mechanical Engineering, Wolaita Sodo University, Soddo, Ethiopia. ¹²College of Engineering, Lishui University, Lishui, Zhejiang 323000, China. ✉email: jitusatpute12345@gmail.com; Dhineshbala91@mepcoeng.ac.in; mesay.dejene@astu.edu.et

study², the PV system performed better electrically when it had an additional cooling arrangement, and the coolant was able to recover thermal energy^{3–5}. This type of hybrid, or photovoltaic-thermal, power generation from a single collector is known as a PVT system. The primary factor that determines a solar collector's reach, longevity, and acceptance in society at large is its efficiency. The literature notes the attempts⁶ to adjust operational and design factors in order to maximize the performance of solar collectors. To assess and improve the performance of the solar system, a variety of optimization approaches⁷ were offered. The Taguchi technology is one of the optimization techniques preferred by the researcher community to control and optimize parameters as per desired performance. The parametric optimization of paraffin wax-based phase change material was performed for thermal storage using the Taguchi methodology⁸. The L9 orthogonal array was selected for a level, three-factor experimental design. The optimization study determined the optimum condition for melting time and time-dependent enhancement ratio for thermal storage. In a recent study⁹, Taguchi methodology was applied to identify influencing parameters that affect the energy performance of PVT systems particularly for the different climatic zones of Morocco. The study showed that optimized values of process parameters not only improved energy (electrical-thermal) performance but also mitigated higher CO₂ as compared to a non-optimized PVT systems. The following table shows the latest survey on the effectiveness of the Taguchi methodology in the solar system to decide and optimize operating and design parameters. The Taguchi-based optimization study was performed for the PVT system by varying coolant and its concentration at varying flow rates and radiation levels¹⁰. In the study, SiO₂-W, Al₂O₃-W, and CuO-W at 0.1, 0.2, and 0.3 as volume concentrations were investigated for electrical and thermal efficiency at 0.55, 1.1, and 1.65 lpm flow rate and 300, 600 and 900 W/m² radiations. It was observed that electrical efficiency mainly depends on irradiance followed by flow rate, volume concentration, and nanofluid while thermal efficiency is affected by the irradiance followed by flow rate, nanofluid, and volume concentration. The compound parabolic collector solar PVT system was optimized using Taguchi methodology¹¹. In the study, thickness, air gap thickness, glass cover thickness, nanoparticles, mass fraction, and PV efficiency were the operating parameters while heat transfer and performance efficiency were the output responses. From the study, it was observed that highest overall performance of the PVT system was 71.1%, at 2 mm glass cover thickness, 10 mm air gap thickness, 21% PV cell efficiency, and 6% nanoparticle mass fraction. The different types of solar collectors such as solar Air heaters with tin cans, solar Air heaters with reflecting mirrors- tin cans, and solar Air heaters with triangular fins were investigated using Taguchi methods for parametric optimization¹². The responses were recorded in terms of outlet temperature of the air, thermal efficiency, pressure drop, exergy, and exergy loss. It was observed that each solar heater performs better in particular hours such as an Air Heater with reflecting mirrors- tin cans during the noon period. A tabulated details of control parameters can be found in Table 1.

It was observed in the literature that many researchers have preferred the Taguchi optimization methodology for performance optimization due to its time-cost effectiveness and ease of result explanation. During the development stage of the system, Taguchi optimization plays an instrumental role in evaluating the optimum performance parameters. It was also observed in the literature that coolant type, low-rate radiation level absorber type; thickness, and flow pattern are key design parameters that affect PVT performance. In PVT design flat plate, circular type thermal absorbers are common thermal absorber type but very few have tried rectangular type of thermal absorber. Additionally, a comparative optimization study among simple PV, circular absorber-based PVT, and rectangular absorber-based PVT was not found in the literature. The present study aims to compare and optimize major effective parameters that improve PVT efficiency and also validate in experimental settings.

The goal of the current study is to use the Taguchi technique to maximize the performance of solar flat panel photovoltaic thermal systems. To determine the importance and ideal arrangement of particular design and operational parameters impacting PV and output water temperatures, the Taguchi technique is used. The water flow rate, incident solar radiation level, and thermal absorber design are among the chosen criteria. The radiation levels used for the performance were in the range of 600–1000 W/m², with three flow rates of 0.04–0.06 kg/sec. The PV module's backside is where the non-absorber, spiral circular, and spiral rectangular thermal

Author	Application	Factor Level	Control parameters
Prabowo et al. ¹³	Air-PVT system	3	Fin-arrangement, height, thickness; air flow rate, heat absorb
Omeroglu et al. ¹⁴	Nanofluid-flat plate collector	4	Solar radiation, mass flow rate, nanoparticle material, nanoparticle ratio
Lin et al. ¹⁵	Air-PCM PVT system	3	Airflow rate, additional wall insulation, type of PCM and its thickness
Kuo et al. ¹⁶	Solar flat plate heater	3	Plate and tube material, no of a tube, diameter, film type, the thickness of insulation
Wenke et al. ¹⁷	Solar air heater-PVT system	2	Material, channel depth, absorber thickness, air gap, covering, flow rate, glass cover, fin, PV efficiency
Özakinet et al. ¹⁸	Air-based PVT system	3	Material, temperature, velocity
Kuo et al. ¹⁹	Water-PVT system	3	Reflector material-size-angle, water velocity, cycle temperature
Yesildal et al. ²⁰	Spray based PV system	3	Spray and Nozzle flow rate, Nozzle to surface distance, radiation
Kazemian et al. ²¹	Water-PVT system	5	Mass flow rate, solar radiation, ambient and inlet temperature, wind speed
Liu Xiaohong et al. ²²	Water-PCM PVT system	3	Mass flow rate, absorber, inlet water temperature, the thickness of PCM
Yakoob et al. ²³	PCM-solar box collector	3	type of PCM, solar radiation, ambient temperature and time
Li et al. ²⁴	PVT-sterling engine	3	fuel composition, fuel/air ratio, and flowrate mixture
Omeroglu et al. ²⁵	Solar flat plat collector	4	solar radiation, exchanger mass flow rate, nanoparticle material, and nanoparticle ratio

Table 1. Recent studies on Taguchi based optimization on PVT system.

absorbers are mounted. Comparative analysis and analysis of variance using the Taguchi methodology are used to determine the role of various factors on the surface temperature and water outlet temperature of PV and PVT systems. The performance equation and statistical significance of the parameters were created based on Taguchi optimization.

Methodology

The Taguchi design is a fractional factorial design that estimates maximum numbers of main effects from minimum runs of the experiment using an orthogonal array. Based on the literature survey, the current study selected the absorber design, solar radiation, and mass flow rate of circulating fluid factors as significant factors that impact performance. In absorber design, no absorber (also called conventional PV) is designed named A1, spiral circular thermal absorber (A2), and spiral rectangular thermal absorber (A3) is made up of the same material and dimensions are preferred, and design is shown in Fig. 1. All the results obtained from the CFX 19.2 simulation are used to optimize. The photograph of the experiment can be found in Fig. 2 The methodology adopted for optimization is, as shown in the flowchart below Fig. 3.

The parameter such as ambient temperature, PV surface temperature, water inlet and outlet temperature, outlet water temperature, PV voltage, PV current and radiation intensity was measured with various instruments. The ambient air temperature was measured with a mercury-based thermometer. The PV surface temperature, inlet-outlet water temperature were measured with a K-type thermocouple. The thermocouples were placed; temperatures were stored and displayed with a temperature acquisition system. The 100 W poly-crystalline PV panels were used for research purposes with reference efficiency of 14.9%. The voltage and current of PV are measured by voltmeter and ammeter respectively. Each set of experiments is recorded after a 30-minute interval, including solar irradiation, water temperature, PV, PVT V-I characteristics, ambient temperature, and surface temperature. The descriptions of Thermal absorber collector systems are enlisted in Table 2. In the experimental work, range of measuring instruments and their uncertainty has vital role hence uncertainty analysis needs to perform. The Table 3 represents instrument used for measuring performance parameter and their individual error.

Table 4 represents the DoE of the experimentation. The design of the experiment is proposed with three factors (n) with three-level (L) variable, number of experiments need to be conducted for three parameters is given by²⁶,

$$\text{No of Experiment} = \text{Degree of Freedom (DOF)} + 1 = n(n-1) + 1.$$

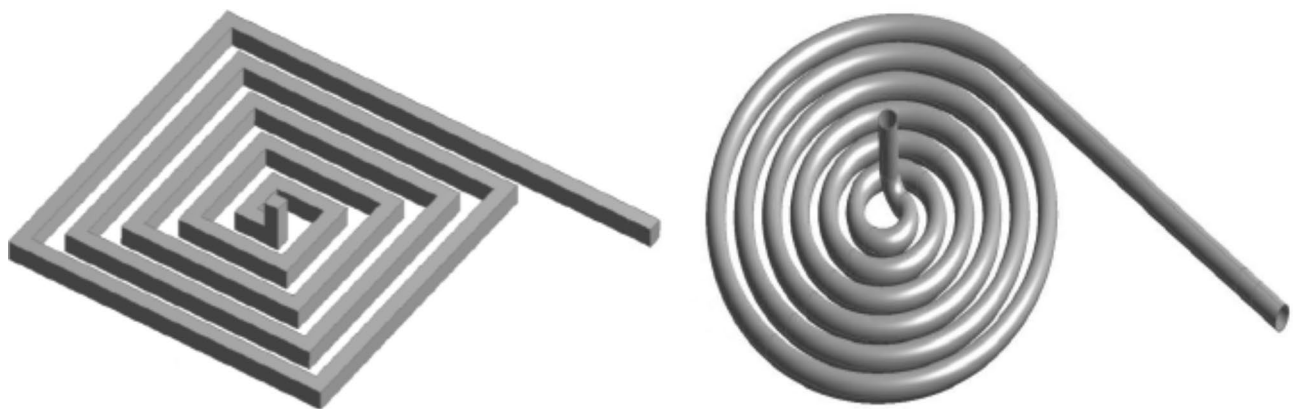
Therefore, L9 Orthogonal Array (OA) is selected for Taguchi Analysis²⁷. The number of experiments is conducted according to L9 OA is reported in table no.

The S/N ratio measures the performance of control factors that affect process variability. The S/N ratios minimize the effect of noise factors and are classified according to preferred characteristics²⁸.

$$\text{Larger the better Characteristics (LTBC)} = -10\log_{10} \left[\frac{1}{n} \sum_{i=1}^n \left(\frac{1}{Y_i^2} \right) \right] \quad (1)$$

$$\text{Smaller the better Characteristics (STBC)} = -10\log_{10} \left[\frac{1}{n} \sum_{i=1}^n (Y_i^2) \right] \quad (2)$$

$$\text{Nominal the better Characteristics (NTBC)} = 10\log_{10} \left[\frac{1}{n} \sum_{i=1}^n \left(\frac{Y_m}{S_v^2} \right) \right] \quad (3)$$



a) Spiral Rectangular Thermal Absorber

b) Spiral Circular Thermal Absorber

Fig. 1. Pictorial views of proposed Thermal absorber configurations for analysis.

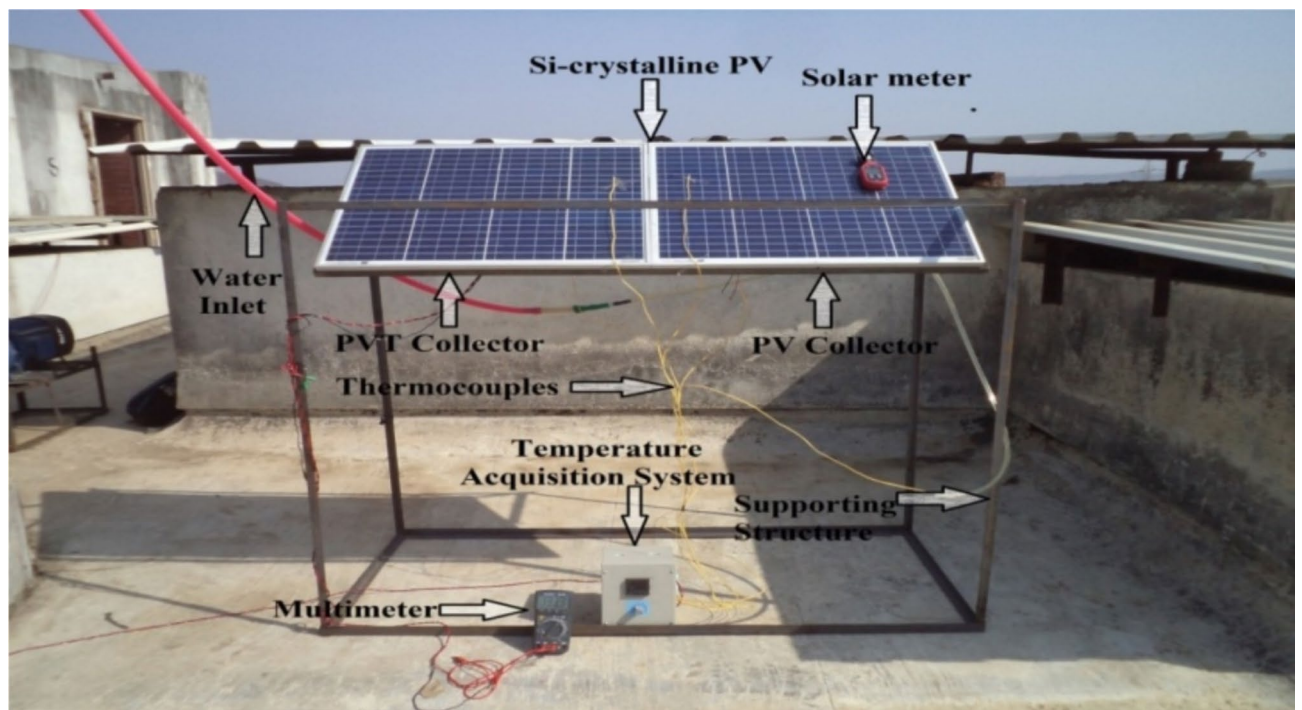


Fig. 2. Experimental test rig.

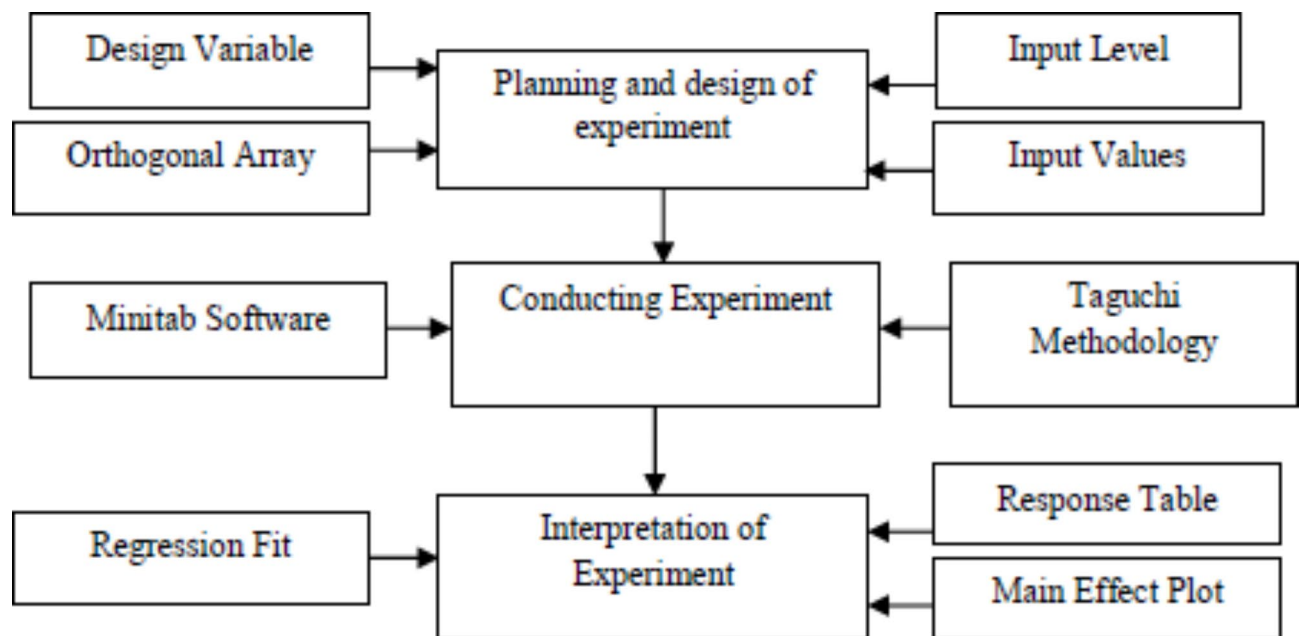


Fig. 3. Flowchart showcasing methodology adopted for Taguchi analysis.

Where Y_i is observed data, Y_m is observed data average, S_y is variation in Y_i , and n is a number of experimental observations.

As discussed in the introduction part, the electrical performance of PV module depends on its instantaneous surface temperature and given by²⁹,

$$\eta_{el} = \eta_{ref} [1 - \gamma (T_{cell} - T_{ref})] \quad (4)$$

Parameter	Spiral circular thermal absorber	Spiral rectangular thermal absorber
Cross-section	Circular	Square
Cross-sectional area	27 mm diameter	25 × 25 mm
Thickness	1 mm	1 mm
Flow pattern	Circular	Rectangular
Length of absorber	8.84 m	8.84 m
Method of joining	Bending	Welding

Table 2. Descriptions of thermal absorber.

Sr no	Quantity	Instrument	Unit	Range	% error
1	Mass flow rate	Rotameter	kg/s	0–1 kg/s	± 1
2	Current	Multimeter	V	200–1000 V	± 2
3	Voltage	Multimeter	A	20 µA–20 A	± 2
4	Temperature	K-Thermocouple	°C	–40–400 °C	± 1
5	Solar radiation	Pyranometer	W/m ²	0–2000 W/m ²	± 2
6	Area	Measuring tape	m	0–10 m	± 1

Table 3. Instruments with their individual uncertainty.

Factors (<i>n</i>)	Level		
	1	2	3
Thermal absorber (A)	No absorber (A1)	Circular spiral (A2)	Rectangular spiral (A3)
Radiation level (<i>S_i</i>) W/m ²	600	800	1000
Mass flow rate (<i>M_f</i>) (kg/s)	0.04	0.05	0.06

Table 4. Factors with their respective levels.

Where η_{ref} is reference efficiency of PV panel as per manufacturer's catalogue (14.9%), γ is constant temperature coefficient and has a value of 0.0045/°C, T_{cell} is the instantaneous temperature of PV panel while T_{ref} is the reference PV surface temperature (25 °C).

Whereas thermal efficiency can be obtained from equation,

$$\eta_{th} = \frac{m_w C_p \int_{t_{in}}^{t_{out}} dT}{I_{sc} \int dA_r} \quad (5)$$

Where C_p is specific heat of water at constant pressure and has the value of 0.4187 kJ/kg-K, and A_r is area of PV panel.

The error analysis is performed using general form of Kline and McClintock method

$$w_R = \pm \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad (6)$$

Where, $R = \{m, T_{out}, T_{in}, A_c, I_g, V_{oc}, I_{sc}\}$ are the average value of parameters.

Hence, by applying Eq. (6) to evaluate uncertainty in the thermal efficiency (η_T)

$$w_{\eta_T} = \pm \sqrt{\left(\frac{\partial \eta_T}{\partial m} m\right)^2 + \left(\frac{\partial \eta_T}{\partial T_{out}} w_{T_{out}}\right)^2 + \left(\frac{\partial \eta_T}{\partial T_{in}} w_{T_{in}}\right)^2 + \left(\frac{\partial \eta_T}{\partial A_c} w_{A_c}\right)^2 + \left(\frac{\partial \eta_T}{\partial I_g} I_g\right)^2} \quad (7)$$

Similarly equation for uncertainty in electrical efficiency is developed and uncertainty is calculated^{30–32}.

Result and discussion

The results obtained from numerical simulation were summarized in a table and utilized to execute Taguchi analysis using Minitab 21.1 software. The methodology was adopted to optimize PV surface temperature and outlet water temperature according to S/N ratios and means calculated by Minitab software.

Exp. run	Parameter of study			Experimental result		S/N ratio	
	Absorber configuration	Solar radiation	Mass flow rate	Panel temperature (T_{panel}) (K)	Water temperature (T_{water}) (K)	(T_{panel}) (dB)	(T_{water}) (dB)
1	A1	600	0.04	323.8	299.1	− 50.205	49.517
2	A1	800	0.05	330.3	299.1	− 50.378	49.517
3	A1	1000	0.06	336.8	299.1	− 50.547	49.517
4	A2	600	0.05	311.2	300.7	− 49.860	49.562
5	A2	800	0.06	317.7	300.9	− 50.040	59.568
6	A2	1000	0.04	326.4	302.5	− 50.275	49.614
7	A3	600	0.06	308.8	300.5	− 49.793	49.558
8	A3	800	0.04	312.5	301.9	− 49.898	49.597
9	A3	1000	0.05	315.5	302.1	− 49.981	49.603

Table 5. Tabulation of experimental design data, result and evaluated S/N ratios.

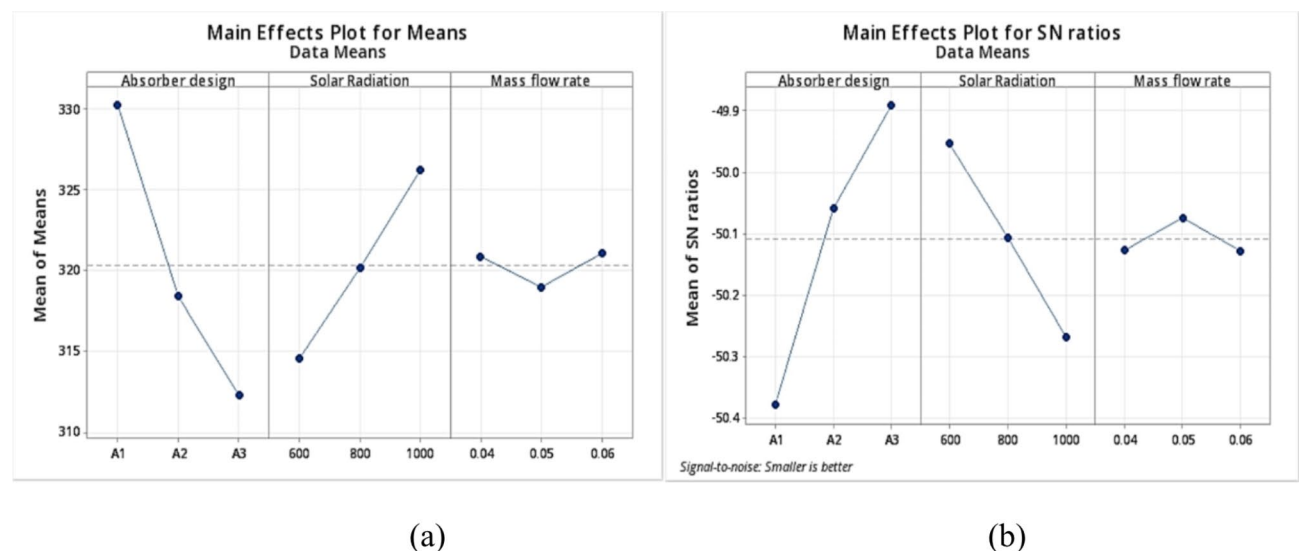


Fig. 4. (a) Plot for means; (b) plot for signal to noise ratio (S/N).

Effect of absorber, radiation and mass flow rate on PV temperature

The response values obtained for PV Temperature by Taguchi designs are summarized in Table 4. The voltage carrying capacity decline at elevated PV temperature resulted in power loss; hence lower the better characteristics were selected. From the main effect plot, it is observed that the third level of factor A (Absorber design), the first level of factor Si (Solar radiation), and the second level of factor Mf (mass flow rate) are higher. Hence, for minimum PV temperature optimum configuration, it can be concluded that the optimum configuration is a spiral rectangular thermal absorber with 0.05 mass flow rates at 600 W/m². From the response table, the value of delta and rank shows that factor A has the highest significance on PV temperature, followed by factor Si and Mf. The importance of lower PV temperature lies in a higher electrical energy conversion by PV panel. At the higher PV surface temperature, voltage output reduces and result in lower electrical power generation^{33,34}. Hence, operating PV at a lower temperature is recommended to ensure better power generation and improve PV panel life.

Effect of absorber, radiation and mass flow rate on water temperature

The results obtained from Minitab 21.1 version software by applying Taguchi design for outlet water temperature are shown in Table 5, Fig. 4. The larger, the better option is selected, and optimum levels of factors are identified using the S/N ratio. Taguchi prediction shows that the third level of factor A, the third level of factor Si and the first level of factor mf are higher. Therefore maximum water temperature at the outlet will be achieved from a spiral rectangular thermal absorber at 0.04 kg/sec with 1000 w/m² radiation. The response table shows that absorber design is the most influencing factor in water temperature trailed by radiation value and mass flow rate. The water circulated from the thermal absorber reduces the temperature of the PV surface and recuperate heat energy to enhance overall energy output³⁵. As A1 is no absorber level, it does not influence thermal efficiency. The rectangular absorber design recovers heat effectively due to better surface area contact with the backside of the PV surface than the spiral circular absorber design. This recovered heat through water can be effectively used for domestic or process heat industrial applications.

Symbol	Parameter of study	Mean S/N ratio				
		1	2	3	Max–Min	Rank
A	Absorber design	– 50.38	– 50.06	– 49.89	0.49	1
S_i	Solar radiation	– 49.95	– 50.11	– 50.07	0.31	2
M_f	Mass flow rate	– 50.13	– 50.07	– 50.13	0.05	3

Table 6. Mean S/N ratios for PV temperature.

Symbol	Parameter of study	Mean S/N ratio				
		Level 1	Level 2	Level 3	Max–min	Rank
A	Absorber design	49.52	49.55	49.58	0.07	1
S_i	Solar radiation	49.55	49.56	49.56	0.03	2
M_f	Mass flow rate	49.58	49.56	49.55	0.03	3

Table 7. Mean S/N ratios for water temperature.

Source	Sum of square	Mean square	F-value	P-value	% contribution
Absorber design	10.52	5.26	458.74	0.00	75.63
Solar radiation	1.88	1.88	164.09	0.00	13.51
Mass flow rate	1.47	1.47	127.35	0.00	10.57
Total	13.61				100

Table 8. Analysis of variance (ANOVA) outlet water temperature.

Analysis of variance (ANOVA)

The ANOVA was executed to predict the implication of the process parameter that affects desired performance³⁶. The result obtained from ANOVA analysis for PV temperature and outlet water temperature were tabulated in Tables 6 and 7, respectively. From Table 6, it was observed that PV surface temperature is significantly influenced mainly by absorber design followed by solar radiation and water flow rate, respectively. The observed percentage contribution of absorber design, solar radiation and the water flow rate was 69.19%, 27.99% and 2.83%, as shown in Table 6. Similarly, the outlet water temperature was influenced mainly by absorber design followed by solar radiation and mass flow rate. The respective percentage contributions were 73.63%, 13.51% and 10.57% for absorber design, solar radiation and mass flow rate. An ANOVA analysis concludes that absorber design is the most significant parameter that affects PV and outlet water temperature.

Modeling and confirmation test

In the current work, regression analysis was performed in Minitab 21.1 software to develop a predictive regression model that gives the relation between predictors and response variables. The mathematical equations obtained from linear regression analysis for PV and outlet water temperatures are follows. Table 8. Analysis of Variance (ANOVA) outlet Water temperature.

For PV temperature,

$$PV \text{ temperature}_{A1} = 306.54 + 0.02912 S_i + 9.2 M_f \quad (8)$$

$$PV \text{ temperature}_{A2} = 394.67 + 0.02912 S_i + 9.2 M_f \quad (9)$$

$$PV \text{ temperature}_{A3} = 288.54 + 0.02912 S_i + 9.2 M_f \quad (R^2 = 97.24\%) \quad (10)$$

For water outlet temperature,

$$Outlet \text{ Water temperature}_{A1} = 299.377 + 0.0028S_i - 49.33M_f \quad (11)$$

$$Outlet \text{ Water temperature}_{A2} = 301.539 + 0.0028S_i - 49.33M_f \quad (12)$$

$$Outlet \text{ Water temperature}_{A3} = 301.740 + 0.0028S_i - 49.33M_f \quad (R^2 = 99.67\%) \quad (13)$$

The efficiency of the developed model is evaluated from the coefficient of determination, i.e. R^2 value. The range of R^2 values varies from zero to one. The R^2 value shows disperse of observed data values around the regression plot, and higher values represent lower variation from the regression model³⁷. The present model's R^2 values for PV and outlet water temperatures are 97.24% and 99.67%, respectively. The developed regression model shows higher R^2 values and good fitment of the model. The residual plot investigates the significance of the coefficient in

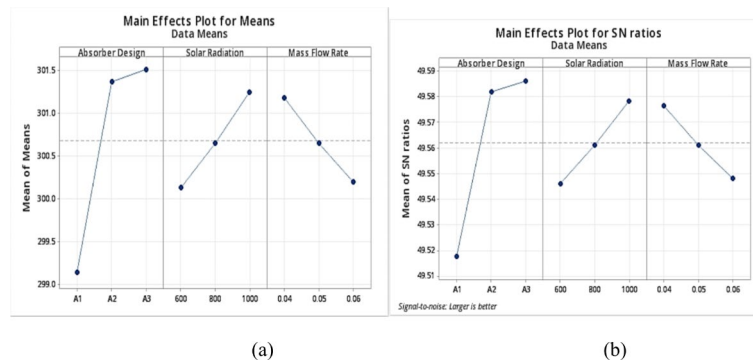


Fig. 5. (a) Plot for means. (b) Plot for signal to noise ratio (S/N).

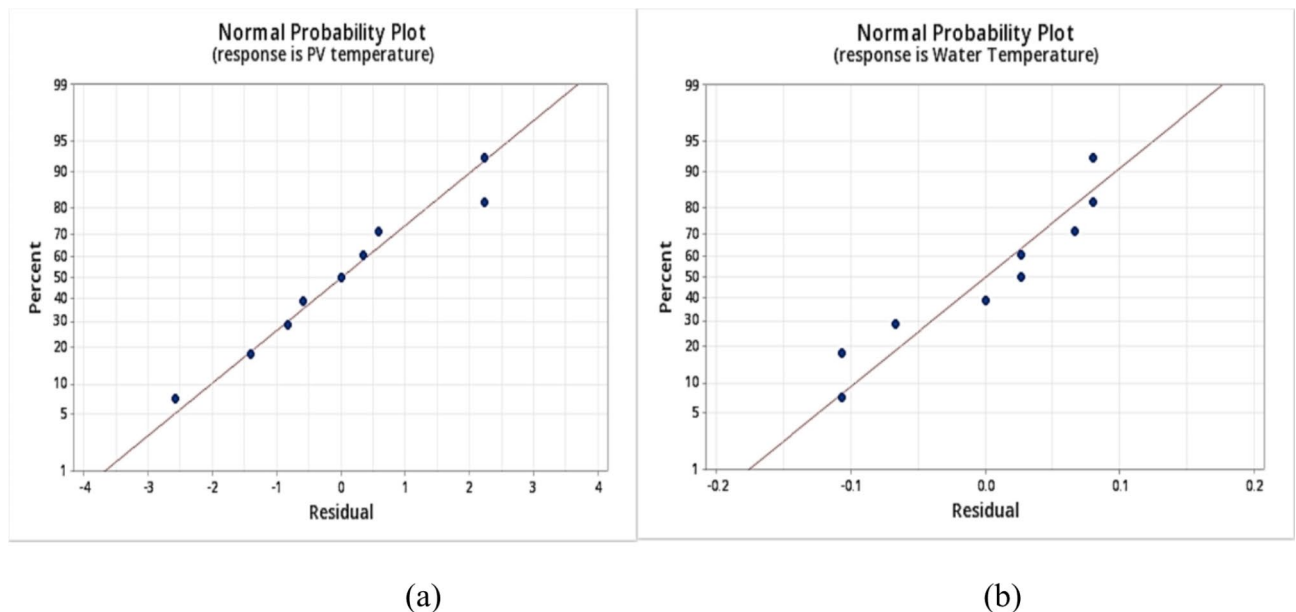


Fig. 6. Residual plot for (a) PV temperature, (b) outlet water temperature.

Source	Sum of square	Mean square	F-value	P-value	% contribution
Absorber design	502.43	251.21	50.07	0.001	69.19
Solar radiation	203.25	203.58	40.58	0.003	27.99
Mass flow rate	20.1	5.017	0.01	0.910	2.83
Total	726.13				100

Table 9. Analysis of variance (ANOVA) of PV temperature.

the predictive regression model. The straight-line residual plot indicates residual errors are normally distributed, and coefficients in regression equations are significant. The residual plot obtained for PV Panel temperature and outlet water temperature is revealed in Fig. 5. From Fig. 6, it was observed that residuals were in proximity to the straight line for T_{panel} and T_{water} , which implies coefficients in the developed model are promising and significant.

The developed mathematical model was validated by conducting a confirmation test, and results were tabulated in Table 9. The test result was taken randomly and compared with predicted results. From the confirmation test, it was seen that the results of analytical analysis were found in good harmony with the predicted result. The percentage error was limited to 0.68% in the case of PV Panel temperature while 0.035% for outlet water temperature. In literature, a similar agreement between analytical and predicted results was found. Table 10. Confirmation results for the developed model.

Run	Analytical (K)		Predicted (K)		Residual (K)		Error (%)	
	(T_{panel})	(T_{water})	(T_{panel})	(T_{water})	(T_{panel})	(T_{water})	R_{Ipanel}	R_{Iwater}
1	323.8	299.1	324.38	299.08	- 0.583	0.067	0.182	0.022
3	336.8	299.1	336.21	299.21	0.584	- 0.067	0.173	0.022
6	326.4	302.5	324.16	302.42	2.234	0.08	0.684	0.026
8	312.5	301.9	312.20	302.00	0.342	- 0.107	0.113	0.035

Table 10. Confirmation results for the developed model.

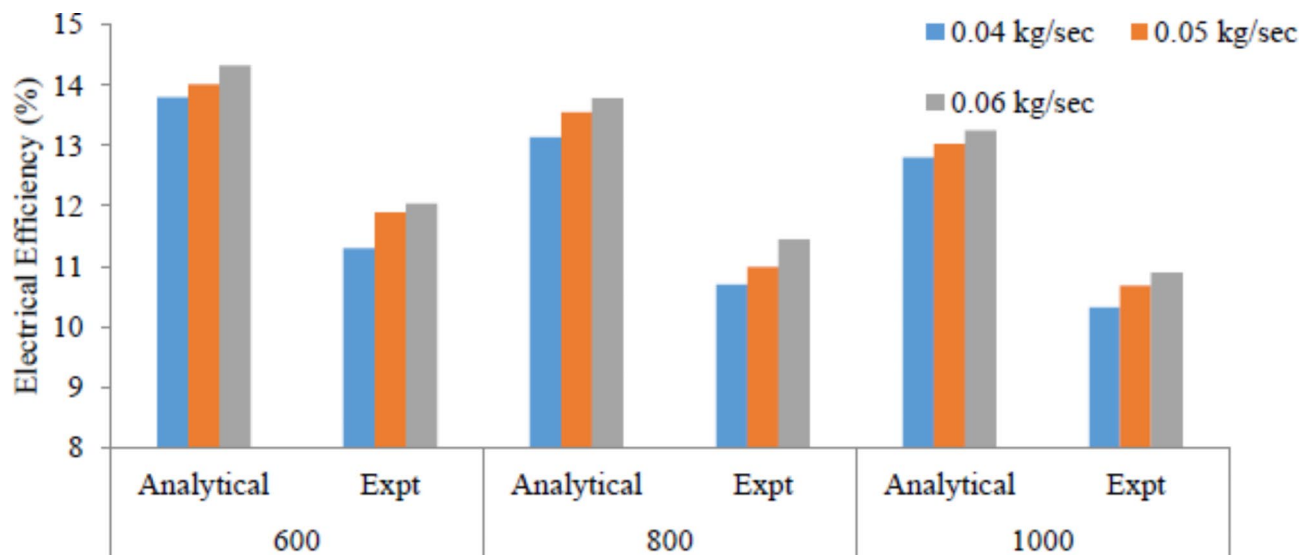


Fig. 7. Variation in the electrical efficiency from spiral circular absorber PVT system.

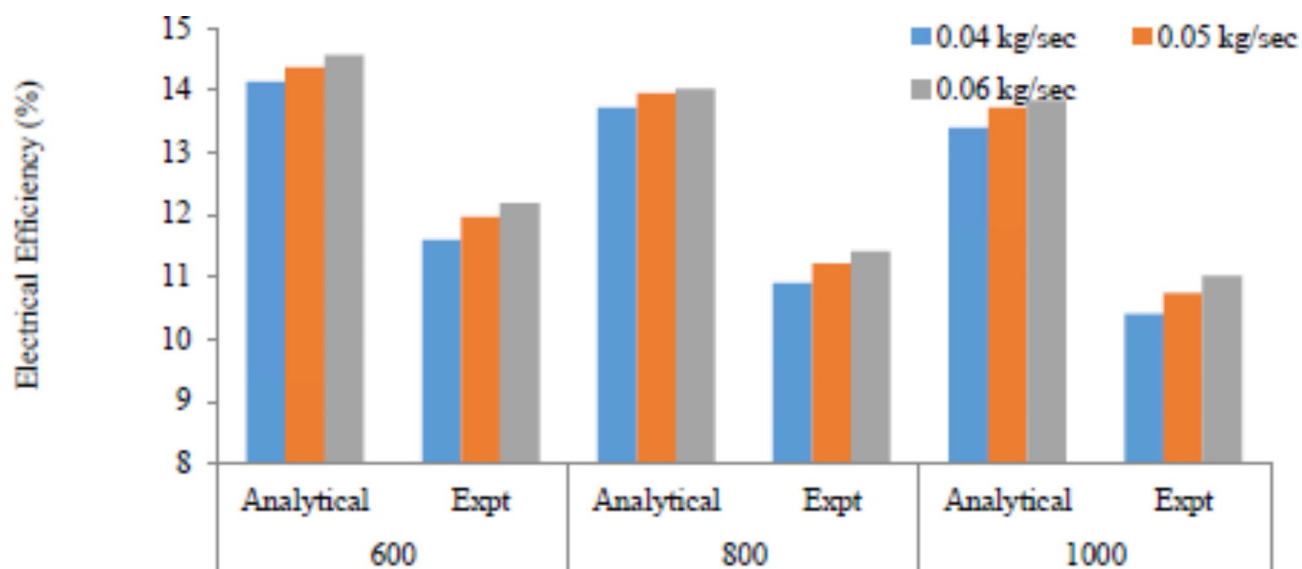


Fig. 8. Variation in the electrical efficiency from spiral rectangular absorber PVT system.

Parametric effect on PV efficiency

The effect mass flow rates and solar radiation on electrical efficiency of conventional PV and PVT collector systems is discussed in Figs. 7 and 8. It was observed that the electrical efficiency of the conventional PV system was lower than the PVT system. This low efficiency were because non-cooling of the PV system at elevated radiation and surface temperature. The electrical efficiency of PV system varied in the range of 12.3–13.17%. The

electrical efficiency of the spiral circular thermal absorber PVT system varied in range from 12.80 to 14.32%. On the other hand, the electrical efficiency of spiral rectangular thermal absorber PVT system varied in range from 13.40–14.57%. This higher electrical efficiency is due to the effective cooling of PV surfaces obtained from water cooling Incorporating spiral rectangular thermal absorber.

The maximum electrical efficiency of 14.57% was observed at the highest flow rate of 0.06 kg/sec under a minimum radiation level of 600 W/m² from spiral rectangular thermal absorber PVT system while minimum electrical efficiency of 12.8% was observed at a lowest mass flow rate of 0.04 kg/sec under maximum radiation level of 1000 W/m² from spiral circular thermal absorber PVT system.

It was clear from the Figs. 9 and 10 that thermal efficiency increases with the rise in water flow. At a higher water flow rate, more heat accumulation results in higher water outlet temperature. The similar trend of result is observed in the literature. The maximum temperature gradient was seen with a spiral rectangular thermal absorber. This gradient is because spiral rectangular thermal absorber maintained surface contact with flipside PV surface, whereas spiral circular thermal absorber maintained line contact. Similarly, rectangular flow resulted in better turbulence due to its geometrical features. The spiral rectangular thermal absorber exhibited higher thermal efficiency due to its better heat extraction features than the spiral circular thermal absorber. Analytically the maximum thermal efficiency of 63.56% was observed at the highest mass flow rate of 0.06 kg/sec under a maximum radiation level of 1000 W/m² while minimum thermal efficiency of 52.20% was observed at a lowest flow rate of 0.04 kg/sec under minimum radiation level of 600 W/m².

It was also seen that experimental electrical and thermal efficiency were lower in all cases than the analytical results. This variation is because analytical treatments were performed at steady-state conditions. The effect of wind speed and heat loss through conduction, convection, and radiation from PV surface is neglected; that affect the electrical and thermal efficiency in the actual case^{46,47}. Additionally, the uncertainty analysis using Kline and McClintock method was carried out and relative uncertainties found to be 0.98% and 2.45% for thermal for electrical efficiency. Table 11 Comparative analysis of the findings with recent works (last three years).

Conclusion

The current study concluded that Taguchi methodology determines optimum conditions that significantly reduce PV temperature and increase the outlet water temperature to increase electrical and thermal efficiency of PVT system. The Study concluded that rectangular absorber design was the dominant and most influential factor for lowering PV and rising water outlet temperatures, followed by solar radiation and mass flow rates. The trade-off was observed about solar radiation for optimum PV and output water temperatures and should be selected as per the desired end-use. From the ANOVA analysis, PV temperature and the output water temperature was significantly affected by Absorber Design with the contribution of 69.13% and 75.63%, respectively. The present study is a foundation that provides spiral rectangular thermal absorber should be preferred over spiral circular thermal absorber, conventional PV system for better performance. In analytical treatment, the maximum thermal efficiency of 63.56% was observed at the highest mass flow rate of 0.06 kg/sec under a maximum radiation level of 1000 W/m² from spiral rectangular thermal absorber PVT system. The maximum electrical efficiency of 14.57% was observed at the highest flow rate of 0.06 kg/sec under a minimum radiation level of 600 W/m² from spiral rectangular thermal absorber PVT system. The experimental electrical and thermal efficiency were lower

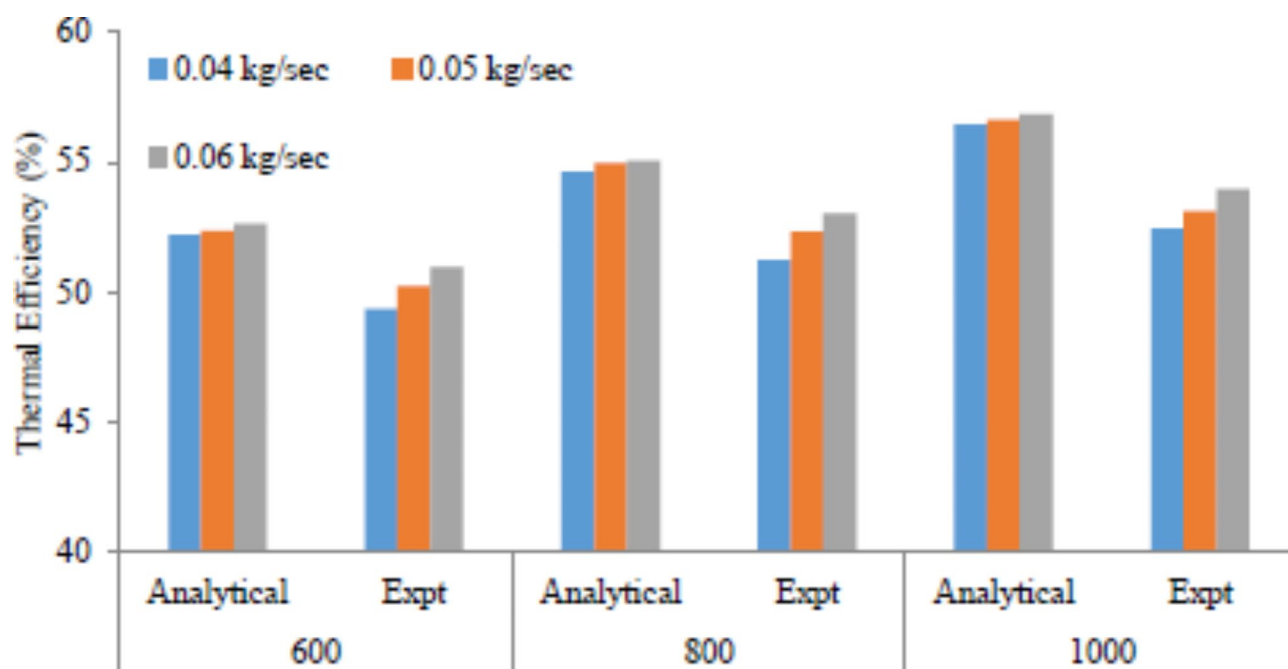


Fig. 9. Variation in the thermal efficiency from spiral circular absorber PVT system.

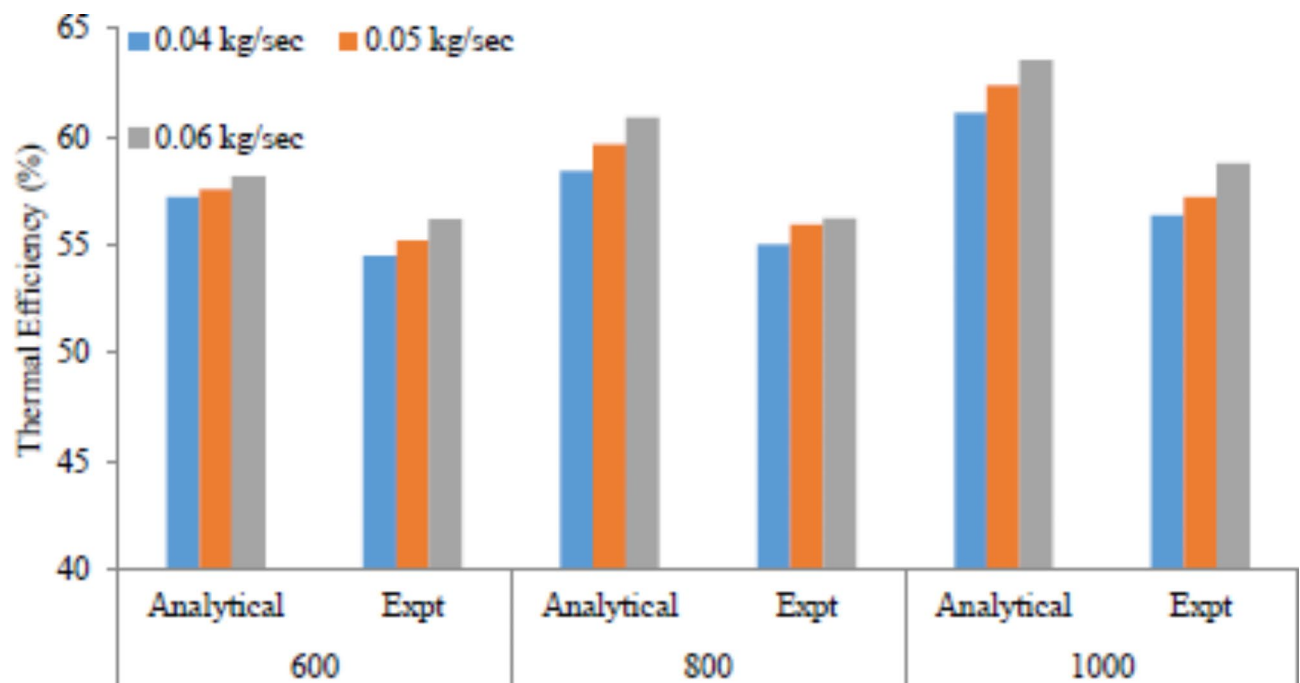


Fig. 10. Variation in the thermal efficiency from spiral rectangular absorber PVT system.

Authors	Descriptions	Analysis tool	Flow rate kg/s	Radiation W/m ²	Efficiency (%)	
					Electrical	Thermal
Misha et al. (2020) ³⁸	Dual oscillating absorber	ANSYS FLUENT	0.034–0.068	600–1000	11.71	59.6
Kazem et al. (2021) ³⁹	Oscillatory/direct flow absorber	Experiment	0.02	500–1000	15.28	60.7
Colombini et al. (2021) ⁴⁰	Harp shape absorbers	Mathematical model	0.03	800	14.0	43.7
Hassan et al. (2023) ⁴¹	Plate absorber	Numerical; experiment	1.02 L/m		14.8	44.5
Azad et al. (2023) ⁴²	Plate absorber	Numerical	0.136	200–1000	11.8	80.4
Ahssan et al. (2023) ⁴³	Serpentine-shaped tube	Experiment	–	550–1050	7.66	89.1
Present work (2024)	Spiral circular, rectangular	ANSYS-Experiment	0.04–0.06	600–1000	14.56	63.5

Table 11. Comparative analysis of the findings with recent works (last three years).

in all cases than the analytical results due to real time atmospheric condition and heat losses. Experimental uncertainties were 0.98% and 2.45% for thermal for electrical efficiency. The analytical and experiment findings were in better agreement in this study, with the highest relative error of 7.52%.

Close conformity was found between predicted and experimental results from the developed regression model as the maximum error is limited to 0.68%. Hence above-developed model could be accustomed to assess the temperature characteristics of Water-PVT systems without conducting trials.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

J.S, S.C & D.B: Conceptualization, E.P.V, Y.F, M.E.M.S Methodology & Formal analysis, Writing—original draft
J.S, S.C.: Conceptualization, Methodology, Formal analysis, Writing—review & editing. R.P, L.P & M.D.A.: Methodology, Writing—review & editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to J.S., D.B. or M.D.A.

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