Optimization of controllable factors for enhancing the efficiency of concentrated photovoltaic-thermal collectors (CPVT): A numerical study and modeling approach under semi humid climatic conditions.

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Abstract

Our study focuses on the optimization of Concentrated Photovoltaic/Thermal (CPVT) systems to enhance their efficiency, reliability, and durability. The objective is to make CPVT systems more cost-effective and environmentally friendly, thereby promoting renewable energy production. The experimental input data utilized in this research study represents a typical area in Algeria characterized by semi-humid climatic conditions. Our investigation specifically explores the influence of three key parameters: the length of fresnel mirrors, the angle between the PV panel and the mirrors, and the thickness of the glass cover. A CPVT model is designed using the finite element method in COMSOL Multiphysics, and statistical analysis techniques such as Design of Experiments (DOEand Analysis of Variance (ANOVA) are employed to identify the most significant factors. The response surface methodology (RSM) implemented in Minitab software facilitates the optimization process to determine the optimal values for each parameter. Our results reveal the substantial impact of the selected parameters on CPVT system performance. By adjusting the factors to their optimal values, a maximum electrical efficiency of 13.14% and thermal efficiency of 82.72% are achieved. This study contributes new insights to the literature by addressing the lack of research on these specific parameters and provides a foundation for the design and optimization of CPVT systems. It highlights the importance of considering these factors in enhancing the overall performance of CPVT technology, paving the way for more efficient and sustainable energy solutions.

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1.Introduction

To address the challenges of increasing energy demand, limited fossil fuel resources, and the need to reduce carbon emissions. In 2020, the global power industry achieved a record-breaking reduction in CO2 emissions of 3.3% (equivalent to 450 Mt). This decline was primarily due to the COVID-19 pandemic, which caused a decrease in electricity demand. However, despite this decrease, renewable energy played a crucial role in reducing overall emissions (Das and Kalita 2020). The renewable energy industry witnessed growth in its contribution to global electricity production, with its share rising from 27% in 2019 to 29% in 2020. Despite the challenges posed by the pandemic, renewable energy maintained its expansion, making a significant impact by contributing 50% more towards reducing emissions in the power sector compared to the previous year (Fikri et al. 2022). So the use of solar energy is becoming increasingly important. While photovoltaic modules offer a way to convert sunlight into electricity, the absorbed sunlight and heat generated from the process can negatively impact their efficiency. To mitigate these effects, various cooling techniques such as air-cooling, water-cooling, and phase change materials have been developed. However, combining thermal cooling with a photovoltaic system not only reduces the temperature of the system but also generates additional energy by utilizing the waste heat from the process. This approach can improve overall performance and contribute to the transition towards renewable and sustainable energy sources.

The CPVT system is an integrated setup capable of harnessing solar irradiation to generate both electrical and thermal energy. It comprises three primary components: an optical device designed to concentrate solar irradiation, a solar-cell module, and an active cooling system.(Murat et al. 2022). The active surface of the solar-cell module receives and focuses the concentrated solar irradiation. To extract excess heat, a suitable cooling device, such as a heat sink, is thermally bonded to the backside of the module. O'Leary and Clements (O'Leary and Clements 1980)) conducted an early study on the formulation of an analytical model for a parabolic trough CPVT system (Karathanassis et al. 2019) .

CPVT systems have gained a lot of attention in recent years as a promising technology for sustainable energy production. As a result, several studies have been conducted to investigate the performance of these systems and develop analytical models to represent them. However, one limitation of these studies is that they often neglect transient effects, which can significantly impact the system's behavior. Transient effects refer to the changes that occur in a system over time, such as variations in temperature or solar irradiance. These effects can have a significant impact on the performance of CPVT systems, particularly during periods of fluctuating solar irradiance or temperature changes. Neglecting these effects can lead to inaccurate predictions of the system's behavior and performance.

To address this limitation, researchers are increasingly focusing on developing analytical models that take transient effects into account (Anand and Murugavelh 2019). These models can provide a more accurate representation of the system's behavior and enable more precise predictions of its performance under different operating conditions. By accounting for transient effects, these models can help to optimize CPVT systems and enhance their efficiency and reliability. Helmers et al (Helmres et al. 2014) developed a theoretical model to assess the impact of operating parameters on the efficiency of a point-focus CPVT system. Specifically, they investigated how the concentration ratio and cell operating temperature affect the system's efficiency. According to their findings, a high concentration ratio (CR > 300) can lead to a reduction in both thermal and electrical losses, resulting in an overall system efficiency of 75%.

By using optical concentrators, sunlight can be focused onto photovoltaic cells in a process known as concentrated photovoltaic (CPV), which reduces the necessary amount of semiconductor material. However, a cooling system becomes necessary as excess heat is generated at higher concentrations. If active cooling is used, the heat can be recovered and turned into thermal energy, resulting in a CPVT system that maximizes energy output (Sharaf and Orhan 2015, Wang et al. 2023). The utilization of the extracted thermal energy is largely reliant on the outlet temperature. .When the temperature is elevated, utilizing heat as a substitute for the heat produced by fossil fuels in industrial applications becomes a favorable choice. This approach is particularly beneficial in regions where electrification poses challenges, as it effectively diminishes CO2 emissions (Zimmermann et al. 2015). The elevated temperature can be harnessed for various purposes, such as generating power using the organic Rankine cycle, providing space heating, desalination of water, absorption cooling for air conditioning, and meeting the demand for domestic hot water (as long as the outlet temperature is above approximately 60°C). The production of electrical energy from unwanted thermal energy is highly desirable. However, this can increase the complexity and cost of the system due to the multiple energy conversions required, which can result in a substantial decrease in the overall efficiency of the system (Jacob et al. 2022).

According to research findings, CPVT systems have demonstrated an impressive overall efficiency ranging from 60% to 80%. (Yang et al. 2018). This high level of efficiency has been observed in locations with high direct normal irradiance, according to (Jacob et al. 2022). Despite this high level of efficiency, the system is reported to have low costs and a short payback time, according to reference (Fikri et al. 2022). Moreover, CPVT systems are versatile in their application range as they can produce both thermal and electrical energy, offering multidimensional output. The concentrated photovoltaic thermal (CPVT) system's effectiveness heavily depends on the cooling medium used. Its primary role is to remove heat from the CPV system, and it's important to understand the critical parameters for selecting the most suitable heat transfer medium for CPVT. Water, air, and oils are considered excellent heat transfer mediums because they possess several desirable traits, such as being safe, fire-resistant, inexpensive, readily available, and having a high heat of fusion. These characteristics make these mediums highly suitable for thermal transport (Georgia et al. 2019).

In our study, our objective is the optimisation of CPVT systems, in order to enhance their efficiency, reliability, and durability. This, in turn, can lead to reduced costs and shorter payback times for the system, making it a more attractive option for renewable energy production. Additionally, by optimizing CPVT systems, we can also help reduce carbon emissions, as they can replace the use of fossil fuels in several industrial and domestic applications.

For this reason, we investigated the impact of various factors on the performance of a CPVT system. Specifically, we focused on three key parameters: the length of fresnel mirrors , the angle between PV panel and the mirrors and finally the thickness of the glass cover. To assess the effects of these factors on the system's efficiency, we first designed a CPVT model using the finite element method in COMSOL Multiphysics. We then used the Design of Experiments Method (DOE) and ANOVA to analyze the data and determine the most significant factors. Finally, we utilized the response surface methodology (RSM) implemented in the Minitab software to carry out an optimization process and identify the optimal values for each of the three parameters. The selection of these parameters for optimization was based on the lack of research on them in the literature. However, our results have shown that the chosen parameters have a significant impact on the performance of the

CPVT system, by changing these factors to their optimal values, we were able to achieve maximum efficiency in the system, resulting in an optimal 13.14% for electrical efficiency and 82.72% for thermal efficiency

2.Classification

Over the last decade, CPVT systems have captured the attention of researchers and developers due to their potential to efficiently convert solar energy into electrical power (Sharaf and Orhan 2015). The PV cells in these systems can produce not only electricity but also thermal energy, and the waste heat generated during this process is harnessed for further use (Daneshazarian et al. 2018). The design of CPVT systems is primarily based on their concentration ratio (CR) and concentrator optics, which determines their efficiency and complexity. Based on these factors, CPVT systems can be categorized into three main types: high concentration linear focus CPVTs, high concentration point focus CPVTs, and low concentration CPVTs, as described in the available literature (Sarbu and Sebarchievici 2017) (Jacob et al. 2022).

According to research of (Kurtz and. Geisz 2010), the concentration ratio (CR) for high concentration systems is above 10x, while for low concentration systems it falls between >1 and

10x. Non-imaging concentrators that have concentration ratios (CRs) below 10 lack the capability to accurately project images of the sun onto the absorber. Instead, they direct solar irradiation from all areas of the solar disk towards the absorber. On the other hand, imaging concentrators with higher CRs are capable of projecting images onto the absorber surface. The solar CR is a measure of a system's ability to concentrate sunlight, and the geometrical concentration ratio remains fixed after manufacturing as it is directly proportional to the system's concentration degree and temperature. By concentrating sunlight, the cost of PV-cell reduces, and the cell efficiency increases while requiring a smaller cell area (Marudaipillai et al.2023).

2.1Type of high-concentration-linear-focus-CPVTs

CPVT systems utilizing high-concentration-linear-focus technology include Linear Fresnel reflector CPVTs, Parabolic trough collector CPVTs, and Linear Fresnel lens CPVTs. These particular types of CPVTs employ a high concentration of sunlight in a linear focus configuration. (Sharaf and Orhan II 2015) . Linear Fresnel reflector CPVTs use curved mirrors arranged in rows to reflect sunlight onto a stationary, linear collector. Compact linear Fresnel reflectors (CLFRs) utilize dual parallel receivers to reduce land space requirements. Experimental tests on a 102-kW thermal LFR system showed maximum efficiencies ranging from 0.28-0.34 for variable airflow rates and 0.26-0.30 for fixed airflow rates. The calculated efficiency was approximately 0.54, while a designed LFRSCHW system achieved a maximum thermal efficiency of 41.2% (Bahrami and Okoye 2018). Parabolic trough collectors focus solar rays onto a receiver tube held lengthways on the trough's focal line, generating temperatures up to 250°C. Optimization using a genetic algorithm on a parabolic trough collector-based CPVT system resulted in electrical and thermal efficiencies around 0.21 and 0.45, respectively. Linear Fresnel lens CPVTs utilize a modified Fresnel lens, which reduces absorption losses and material requirements. A study on a solar thermal system employing a Polymethyl Methacrylate (PMMA) acrylic Fresnel lens with dual-axis tracking capabilities showed a global efficiency below 20% due to various energy losses, with optical losses accounting for 47% of the total losses (Shadmahri et al. 2023).

2.2 Type of high-concentration-point-Focus-CPVTs

High concentration point focus CPVT systems concentrate sunlight onto an absorber located at the focal point of a concentrator. Parabolic dish collector CPVTs consist of mirrors and an absorber positioned at the dish's focal point, achieving temperatures of 1500°C or higher without the need for heat transfer fluid or a heat exchanger. The effectiveness of a solar PDC-based plant in Italy was evaluated, generating 5440 kWh in 1326 working hours (Fu et al. 2023). Heliostat-field-central-receiver-CPVTs utilize a tower and tracking reflectors to concentrate sunlight, with the potential to produce electricity or store thermal energy. Coupling the system with a Rankine or Brayton cycle can improve its performance. In a wind-solar poly generation system, a CPVT system coupled with a wind turbine achieved high thermal and exergy efficiency, outperforming a CSP system coupled with a wind turbine. Further studies explored the optical efficiency improvement of a parabolic trough collector and the feasibility of using a sodium-cooled solar receiver with a heliostat aiming strategy for long-term power output (Sharaf et Orhan 2018). Spot Fresnel lenses in CPVT technology demonstrated higher thermal effectiveness, delivering 7-12% higher energy output per unit due to extended contact time and higher concentration ratio. The utilization of a point focus Fresnel lens for thermal energy storage demonstrated an annual thermal efficiency ranging from 87% to 97%. In the case of a 30 kW hybrid CPVT system with a point focus Fresnel lens, testing revealed a PV efficiency of 30% and an instantaneous thermal efficiency of 30%. As a result, the system achieved a net solar energy conversion efficiency surpassing 60%. (Singhy et al. 2021).

2.3 Type of Low concentration CPVT

Low concentration CPVT systems include the compound parabolic concentrator (CPC), booster reflector, and luminescent concentrator, among others. CPCs require a large receiver to collect all incident solar energy due to their parabolic lines with two different focuses. Solar adsorption refrigeration systems utilizing Compound Parabolic Concentrators (CPCs) have demonstrated notable improvements in the coefficient of Performance (COP) of the adsorption cycle when compared to conventional mass transfer modes. (Zaho et al. 2020). Proposals have been made for other low-concentration CPVT systems, such as the compound hyperbolic concentrator-trumpet photovoltaic-thermal system (CHCT-PVT), with the aim of enhancing electrical efficiency by reducing the size of the reflector (Alzahrani et al. 2021). Experimental investigations of various low concentration CPVT collectors have shown high overall heat loss coefficients and achieved impressive thermo-optical and electrical efficiency. Adsorption chillers driven by CPCs have also shown improved COPs when using activated carbon in the adsorbent bed.

3. CPVTs system design

3.1 CPV design

There are various designs proposed for concentration photovoltaics (CPV), such as the V-trough concentrator utilizing flat-plate mirrors, the optical performance of this concentrator was simplified and analyzed by (Fraidenraich and Almeida 1991). The findings revealed that the optical efficiency of diffuse radiation is primarily determined by the concentration ratio (CR) while showing a slight dependence on the trough's vertex angle.Therefore, constructing V-trough cavities with larger trough angles would be more cost-effective. (Hermenean et al .2009) conducted geometric modeling and numerical simulations of CPV to determine optimized parameters that can maximize the incident radiation on the PV cell while minimizing the system's size. The researchers observed an increase in concentration ratio (CR) as the incident angle increased, but they found that the radiation was independent of the tracking step. This led them to conclude that CR growth was primarily influenced by the incident angle. They proceeded to examine a concentrator system that involved attaching mirrors to a photovoltaic (PV) panel equipped with an equatorial tracking system. Their analysis focused on studying the correlation between the width of the mirror and other relevant factors, the incident angle of the sunlight, and the inclination angle of the mirrors. The results showed that the optimal mirror inclination angle was 65°, and the concentration ratio (CR) was 2.2x when the reflected rays fully covered the PV surface twice. When minimizing the 5° inclination angle, the CR was 1.6x. In a practical field study conducted by (Ya'acob et al. 2014) in Selangor, Malaysia, they conducted a comparison between the performance of a tracking mechanism and a fixed mirror concentrator on PV arrays. Their findings revealed that the mirror's contribution was significantly higher than that of the tracking system, resulting in a daily efficiency increase of 14%. (Rosales et Gutierrez 2016) created a mathematical model that provided a versatile 2D geometric representation of the impact of direct solar radiation on a V-trough system, incorporating tracking parameters. They found that a V-trough system with two mirrors of the same width could achieve a concentration ratio of 2 suns while reaching an average effective concentration ratio of 0.61 during the daytime when the system remained fixed. Moreover, through a combined approach of optical, thermal, and electrical modeling, (Bahaidarah et al. 2015) conducted a study to enhance solar radiation absorption and energy generation in a V-trough system. The results demonstrated the system's suitability for improving energy output.

3.2 Cooling system design

In highly concentrated photovoltaics (CPV), it is necessary to employ active cooling to prevent overheating of the CPV cell. While most point focused CPVTs prioritize capturing waste heat over the cell rather than using spectral beam splitting, this is due to the additional power required for the secondary thermal receiver, which can decrease the overall system efficiency. On the other hand, multi-junction photovoltaic (MJPV) cells are capable of capturing a wider range of light wavelengths compared to silicon cells, reducing the need for beam splitting. According to a study conducted by. (Vincenzi et al. 2014) it was discovered that MJPV cells demonstrated higher system efficiencies compared to beam splitting designs utilizing photovoltaic (PV) cells optimized for specific wavelengths. The reason behind this performance advantage was attributed to the MJPV cell's ability to absorb a broader spectrum of sunlight, allowing it to harness a greater portion of the available solar energy. On the other hand, (Escarra et al. 2018) suggested that beam splitting enables the thermal output temperature to be unrestricted by the temperature of the PV cell, unlike waste heat recovery (WHR). (Zhang and Zhang 2015) indicates that the primary parameter for assessing the performance of the cooling system is the thermal resistance of the heat sink. Extensive research has been conducted on microchannel/minichannel cooling designs, as highlighted by (Kumar et al. 2018). Their study demonstrates the effectiveness of such cooling designs for highly concentrated photovoltaic/thermal (HCPVT) systems. Additionally, (Jenkins et al. 2017) emphasize that microchannels provide an enhanced surface area that promotes efficient heat transfer while minimizing excessive friction. The studies conducted by (Husain et al. 2016) and (Vilarrubi et al. 2018) suggest that micro-pin-fin heat sinks offer higher heat transfer rates but at the cost of increased pressure drops. (Dong et al. 2018) indicate that innovations in microchannel designs often focus on the shape of the channels or the design of the manifold. To enhance the performance of microchannel cooling systems, (Gilmore et al. 2018) and (Cameron et al. 2022) affirm that hybridization with impinging jets can be beneficial. However, (Chehreh 2021) warns that poorly manufactured impinging jets can lead to turbulence, adversely affecting the formation of a thin boundary layer and reducing heat transfer effectiveness.

When it comes to cooling systems for concentrated photovoltaic/thermal (CPVT) setups, the most common types are air-cooled and water-cooled systems, as stated by (Afram and Abdullah 2023).

4. Methodology

The efficiency of concentrated photovoltaic-thermal (CPVT) collectors was explored through numerical investigation and modeling of controllable parameters and conducted in the context of the semi-humid climatic conditions of Souk Ahras, Algeria. The study focused on exploring the impact of various parameters on the performance of concentrated photovoltaic-thermal collectors in this specific region. Souk Ahras is located at geographical coordinates of 36°17'15" north and 7°57'15" east, experiencing a semi-humid climate. The climatic parameters considered for this study were a solar irradiance of R = 1400 W/m² and a reference temperature of Tref = 25°C. By analyzing the controllable parameters, the study aimed to optimize the efficiency and effectiveness of concentrated photovoltaic-thermal collectors in harnessing solar energy in Souk Ahras."

4.1 Comsol modeling

The system employed the COMSOL physics modules, specifically the geometrical optics interface and conjugate heat transfer. These modules encompass the essential physical principles required to investigate the interaction between optical rays and the system, as well as heat transfer in solid and liquid through conduction, convection, and radiation. When considering the geometry boundaries, the primary focus was on reflecting the rays off the mirror surfaces. Specular reflection, which exhibits a reflectivity of one, was selected as the type of reflection.

By utilizing the geometrical optics interface, the simulation accounted for the behavior of light rays as they interacted with various components of the system. This allowed for a comprehensive analysis of the optical performance. Additionally, the conjugate heat transfer module incorporated the transfer of heat between different media. This comprehensive approach enabled a thorough examination of the thermal behavior and efficiency of the system.

The utilization of the COMSOL physics modules, including the geometrical optics interface and conjugate heat transfer, provided a robust framework for analyzing the system. By considering the principles of optics and heat transfer, the simulation accurately captured the behavior of optical rays and the associated thermal effects (El Hocine et al. 2017).

4.2 CPVT Mathematical model and simulation

In this research study, the performance of a specific type of solar energy system called a concentrator photovoltaic/thermal (CPVT) system was analyzed. The CPVT system used in this study was equipped with a V-trough concentrator that had a parabolic shape. The parabolic design of the concentrator meant that it was not very effective at capturing diffuse radiation, which is scattered sunlight that does not come directly from the sun, but rather relies primarily on reflected beam radiation to produce energy at the absorber.

The electrical efficiency of the photovoltaic (PV) panel employed in concentrated photovoltaic/thermal (CPVT) systems is influenced by several factors, such as the concentration ratio (CR) and the temperature of the PV cell (T_{pv}). The correlation between these factors and the electrical efficiency can be determined through a dedicated equation:

$$\eta_{el} = \eta_{T_{ref}}[1 - \beta_{ref}(T_c - T_{ref})] \quad (01)$$

The thermal energy derived from the coolant water can be described in the following manner:

$$E_{th} = \dot{m}C_p\, w(T_{out} - T_{in}) \quad (02)$$

The mass flow ($\dot{m}$) rate is calculated using the following equation:

$$\dot{m} = \rho U_0 A_{fc} \quad (03)$$

The inlet velocity per unit cross-sectional area (A_{fc}) is defined as follows:

$$A_{fc} = \pi \frac{D_i^2}{4} \quad (04)$$

Where D_i is the tube inner diameter.

The PVT thermal efficiency is defined as:

$$\eta_{th} = E_{th}/E_c \quad (05)$$

4.3 CPVT system Design

The figure 1 presented in the study illustrates the geometry of the CPVT system that was investigated. This system combines a concentrator system based on Fresnel mirrors made of Polymethyl methacrylate) (PMMA) with a PVT system composed of a PV model and a solar collector model. The purpose of the concentrator system is to concentrate and direct the incoming sunlight onto the PV cells, thereby increasing the amount of electrical power generated per unit area. The V-trough concentrator has a parabolic shape that allows it to capture and focus the direct beam radiation, while minimizing the amount of diffuse radiation that reaches the absorber. This feature makes parabolic concentrating collectors more efficient than flat plate collectors in high irradiance conditions, but also more sensitive to the tracking accuracy and the shading effects caused by the receiver's edges.

The PV model used in the study is a typical monocrystalline silicon cell with an electrical efficiency of 14.47%, which is a common value for commercial PV panels. The PV cells are encapsulated in a layer of ethyl vinyl acetate (EVA) to protect them from moisture and dust. A layer of Tedlar serves as the back sheet to prevent moisture from entering from the back side of the panel. A thermal paste is applied between the PV cells and the back sheet to enhance the thermal contact and facilitate heat transfer from the cells to the collector. The PV cells are cooled by a sheet and tube collector, which is attached to the back side of the panel. The collector consists of a serpentine-shaped flow channel that allows water to flow through it and extract the heat generated by the cells. The collector is made of copper, which has a high thermal conductivity, to enhance the heat transfer from the cells to the water. The water is pumped from a storage tank and circulated through the collector, where it absorbs the heat and gets heated up. The heated water is then directed to a heat exchanger, where it transfers its heat to a secondary fluid or to the ambient air.

Table 01: Material and thermal characteristics of the CPVT collector.

Materials Glass	Layer	Thermal Density	Thermal Conductivity [W/(mK)]	Heat capacity at constant pressure	Thickness (mm)

		[kg/m3]		[J/kg K)]	
Glass	Top cover	2210	1.4	730	3
EVA	Encapsulant	950	1	1	0.8
Silicon	Solar cell	2329	130	700	0.1
Tedlar	Bottom cover	1190	0.18	1470	0.05
Thermal paste	Conductor	63	1.9	2000	0.03
Fresnel mirrors	Concentrators	1200		2300	1

The second table presents the characteristics of CPV module

Table 02: Characteristics of the CPV module

Item	Values
Cell material	p-Si monocrystalline
Size of the PV module	1205 mm×545 mm
Size of cell	125mm x 125mm
Number of cells	36 cells in a series

Module Efficiency	14.47%

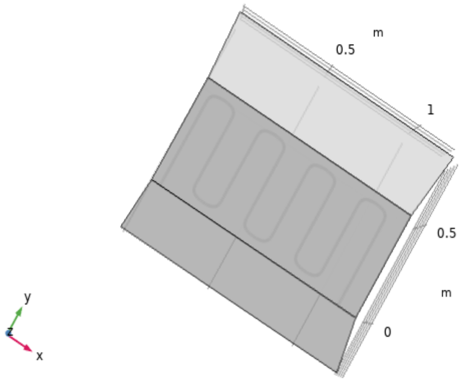


Figure 01 : Design of Concentrating Photovoltaic thermal system

The 3D numerical simulation was conducted using COMSOL Multiphysics, a widely used software based on the finite element method (FEM), which is a commonly employed technique in engineering and mathematical modeling. The objective of the simulation was to analyze the temperature distribution of both the PV panel and the refrigerant fluid within the CPVT system. The finite element method is a numerical approach for solving partial differential equations (PDEs), which enables the accurate computation of complex systems. The simulation results were presented in Figure 02, illustrating the temperature distribution across the PV panel and the refrigerant fluid. This visual representation is crucial in comprehending the system's performance. By leveraging these simulation outcomes, the design and performance of the CPVT system can be optimized. The utilization of numerical simulations is a well-established practice in the design and optimization of CPVT systems, facilitating a comprehensive analysis of their performance and aiding in the identification of areas for enhancement.

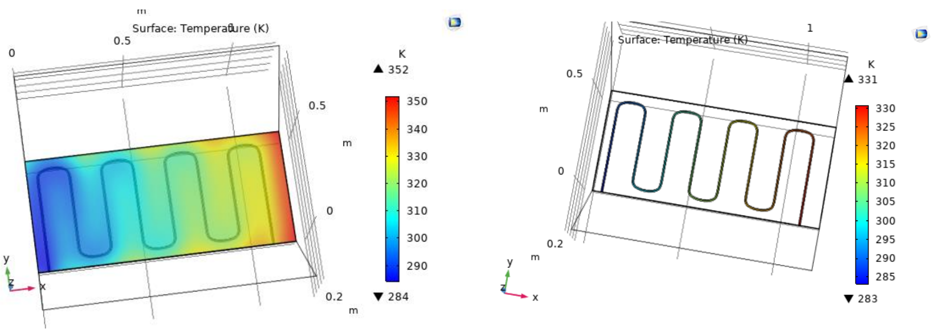


Figure 02: (a) Temperature profile of CPVT panel for its surface (b) Temperature profile of the inlet fluid in CPVT channel

4.3.2 Mesh generation

In our work, mesh generation played a crucial role in the numerical analysis of the CPVT system. Mesh generation is a computational technique used to discretize a complex structure into smaller, more manageable elements. Specifically, we employed the finite element method, which divides the CPVT system into finite elements to solve the partial differential equations.

Within the COMSOL Multiphysics software, we utilized the predefined mesh sequence to create meshes for the CPVT system. The mesh elements were generated in a way that increased their density at the system's borders. This approach enhanced the accuracy of heat transfer and flow calculations within the system.

For our model, we employed both free tetrahedral and free triangular mesh configurations. These settings resulted in a total of 112,354 elements for the free tetrahedral mesh and 53,786 elements for the free triangular mesh. The use of these meshes allowed us to capture the intricate details of the CPVT system and accurately analyze its performance.

4.3.3 Design of experiment

The design of experiments (DOE) utilizes a computational approach commonly employed to examine the correlation between variables that impact the outcome of a process. In our particular case, we utilized DOE to identify the specific factors and their respective impact on process efficiency. Essentially, DOE helps us understand the cause-and-effect relationship by exploring the effects of various covariate factors. DOE is an essential tool for gaining insights into a system, process, or product, allowing us to estimate its optimal operating conditions. The primary benefits of employing DOE include the ability to attain an optimal solution through simultaneously studying multiple factors, thus reducing the need for extensive real-world experiments and tests. Additionally, conducting different DOEs in a computationally efficient manner enhances the accuracy of the results. Moreover, DOE facilitates the study of interactions and correlations among the factors involved (Terrab et al. 2022).

This section focuses on optimizing three key factors related to the optical properties of the CPVT system. Table 03 outlines the variables that can be adjusted, including the length of the Fresnel mirrors, the angle between the PV panel and the Fresnel mirrors, and the thickness of the glass cover. The values of these factors are predetermined, and the aim is to improve the performance of the CPVT system by adjusting them. By optimizing these factors, we can enhance the efficiency and performance of the CPVT system.

Table 03: Factors chosen in the factorial design of ANOVA analysis.

Code	Factor	Level

		(-)	(0)	(+)
A	length of Fresnel mirrors (mm)	272.5	545	817.5
B	Angle (Θ)	120	140	160
C	thickness of glass cover (mm)	1	3	5

5. Results and discussion

Table 04 presents the CPVT configurations examined in the study along with the corresponding thermal and electrical efficiency results. The values reported in this table were derived using equations 7 and 8. Notably, COMSOL was employed for the calculations T_{out} and T_c for a given T_{in}.

Table 04: Calculated results.

Taille of mirrors	Angle of mirrors	Thickness of glass cover	Electrical efficiency	Thermal efficiency
272,5	120	1	12,829102	81,67555649
272,5	140	3	12,90724	81,52073761
272,5	160	5	12,946309	81,34871664
545	120	3	12,90724	81,50353552
545	140	5	12,985378	81,36591874
545	160	1	12,946309	82,31203408
817,5	120	5	12,90724	81,45192923
817,5	140	1	13,024447	82,52706029
817,5	160	3	13,141654	82,71628336

5.1 Main effect plot

Figure 03 and 04 illustrate the impact of various parameters on the electrical and thermal efficiency of CPVT. As shown in Figure 03, the results indicate that increasing the length of the Fresnel mirrors (parameter A) or the angle between the PV panel and the Fresnel mirrors (parameter B) results in an improvement in electrical efficiency. Additionally, the thickness of the glass cover has a positive effect on electrical efficiency up to a maximum value of 3 mm. Beyond this point, further increases in glass cover thickness lead to a decline in electrical efficiency. In contrast, Figure 04 shows that increasing the length of Fresnel mirrors (parameter A) and the angle between the PV panel and the Fresnel mirrors (parameter B) have a favorable impact on thermal efficiency. However, the thickness of the glass cover has a detrimental effect on thermal efficiency, meaning that increasing the thickness of the glass cover will lead to a decrease in thermal efficiency.

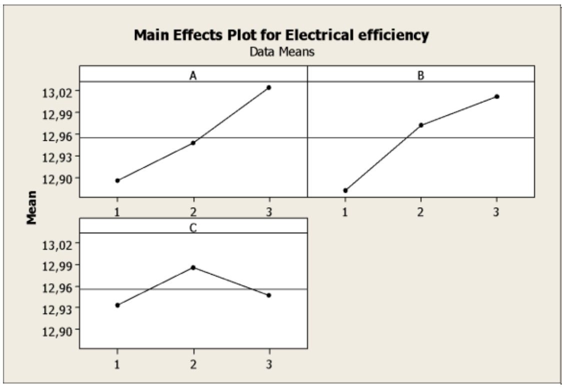


Figure 03: Main effect plots of CPVT parameters on the electrical efficiency.

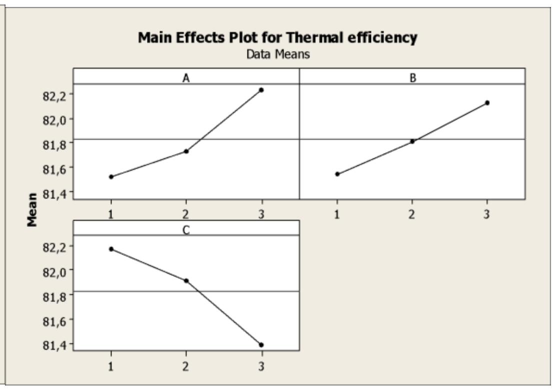


Figure 04: Main effect plots of CPVT parameters on thermal efficiency.

5.2 Interaction plot

This methodology allows researchers to evaluate the effects of various parameters on electrical and thermal efficiencies, and to understand how the interactions between these parameters further influence the overall performance. The significance of the second categorical factors lies in their impact on the electrical and thermal efficiencies, and the manner in which the relationship between these factors affects these efficiencies. Every plot demonstrates the variations, by employing three lines, the study investigates the impact of a factor at three different levels (red, , green and black), with the x-axis representing the varying factor and the y-axis representing efficiency. In order to examine the impact of each variable on all other variables and assess the effects of their interactions on electrical and thermal efficiencies, one parameter is kept constant while the remaining variables are individually adjusted (panel rows), and efficiency values are calculated for each parameter combination. When the lines are parallel, it indicates the absence of any interaction (Gilmore et al. 2018).

Figure 05 demonstrates significant interaction effects for electrical efficiency. When the length of Fresnel mirrors (A) is set to a low value of 272.5 mm, increasing the angle (B) and the thickness of the glass cover (C) leads to an increase in electrical efficiency. However, when the length of Fresnel mirrors (A) is set to a middle level of 545 mm, the best electrical efficiency is achieved at the middle level of the angle between mirrors and PV panel (B), while the electrical efficiency decreases to a minimum when the thickness of the glass cover is set to 3 mm at the middle level. When the mirrors' length is set to a high level of 817.5 mm, increasing the angle between mirrors and PV panel (B) improves the electrical efficiency. On the other hand, the best electrical performance is obtained at the middle level of the thickness of the glass cover (C). Taking into account the interaction between the diameter of the pipe (C) and the length of the pipe (B), for a low value of factor (B), the electrical efficiency increases as factor (C) is increased. When factor (B) is set to the intermediate level, the electrical efficiency reaches its lowest point at the same level of factor (C). Conversely, when factor (B) is set to a high value, the optimal electrical performance is obtained at the intermediate level of factor (C).

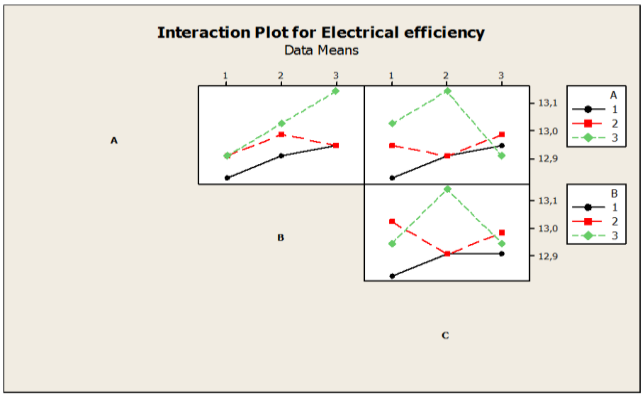


Figure 05: Interaction effect plots of the CPVT parameters on the electrical efficiency.

Figure 06 displays the interaction plots illustrating the thermal efficiency. When the length of Fresnel mirrors is set to a low level, the thermal efficiency decreases as factors (B) and (C) decrease. However, when factor (A) is set to the intermediate level, the optimal thermal performance is achieved with a high value of factor (B) and a low value of factor (C). Additionally, when factor (A) is set to a high level, the thermal efficiency increases with increasing factor (B) and decreases with decreasing factor (C). Examining the interaction between the pipe diameter (B) and the pipe thickness (C), we observe the following patterns:

For low and intermediate levels of factor (B, the thermal efficiency decreases as the value of factor (C) increases. When factor (B) is set to a high level, the highest thermal efficiency is attained at the intermediate level of factor (C)

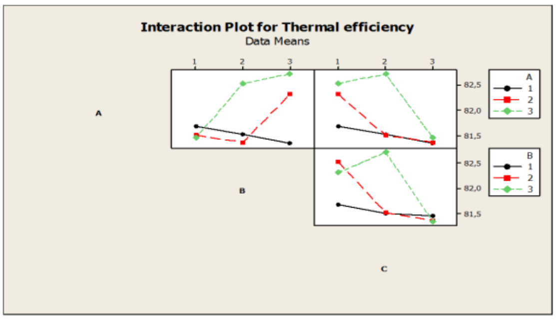


Figure 06: Interaction effect plots of the CPVT parameters on the electrical efficiency

5.3 Contour plot results

The contour plots presented in Figure 07 illustrate the correlation between the analyzed factors and electrical efficiency. The plots clearly demonstrate that attaining a high electrical efficiency necessitates setting factors (A) and (B) to high levels, while maintaining factor (C) at moderate levels. The densely clustered contours in these regions indicate the substantial influence of these factors on the electrical efficiency.

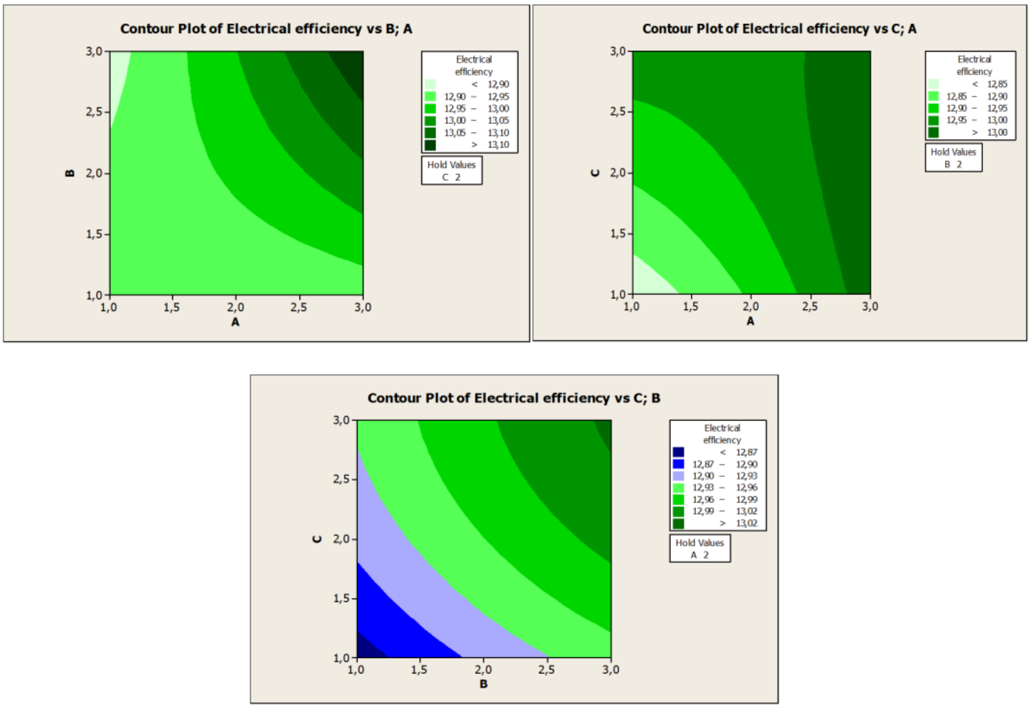
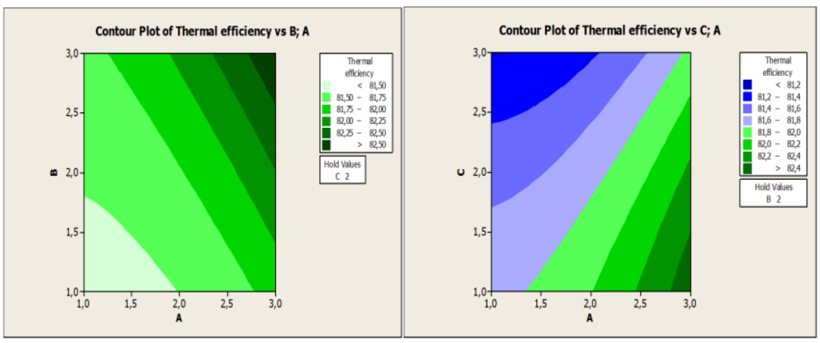


Figure. 07: Contour plots of electrical efficiency of CPVT parameters

In a similar vein, the contour plots presented in Figure 08 depict the relationship between the analyzed factors and thermal efficiency. The plot clearly demonstrates that factor (A) and factor (B) exert a significant influence on thermal efficiency, with higher values achieved when these factors are set at higher levels. Conversely, the contours for factor (C) are more widely spaced, indicating a relatively lower impact on thermal efficiency.



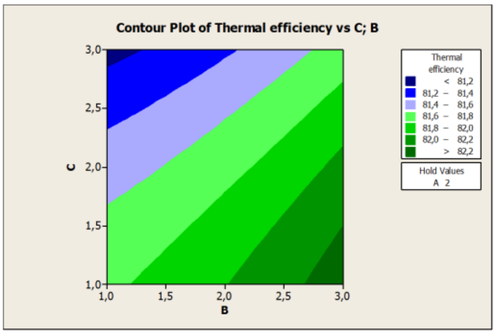
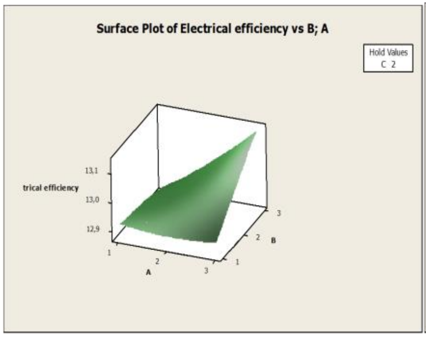


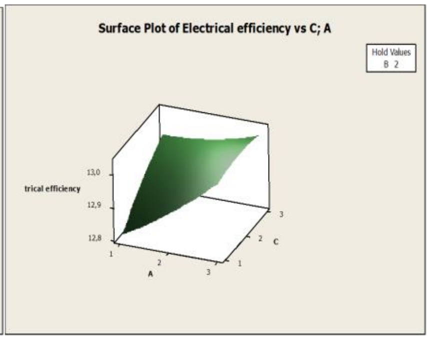
Figure 08: Contour plots of thermal efficiency of CPVT parameters.

A surface plot is a type of 3-dimensional (3D) graph that is used to visualize and display data that varies over two independent variables, usually represented on the x and y-axis, and a dependent variable represented on the z-axis. In a surface plot, the data is usually represented as a continuous surface that is formed by connecting a series of data points using lines or curves.

A surface plot is a 3-dimensional (3D) graph that is used to represent and visualize data that varies over two independent variables, typically represented on the x and y-axis, and a dependent variable represented on the z-axis. The data is usually represented as a continuous surface that is formed by connecting a series of data points using lines or curves 1 2. A surface plot is a useful tool for investigating desirable response values and operating conditions 3. It is a companion plot of the contour plot and is similar to the wireframe plot, but each face of the wireframe is a filled polygon, which helps to create the topology of the surface being visualized1. The axes 3D present in Matplotlib's mpl_toolkits.mplot3d toolkit provides the necessary functions used to create 3D surface plots1. The function plots the values in matrix Z and creates a three-dimensional surface plot that has solid edge colors and solid face colors4. Surface plots are created by using the ax.plot_surface function, where X and Y are 2D arrays of points of x and y, while Z is a 2D array of heights1.

Figure 09 shows the surface plots for the electrical performance of CPV panels as a function of analyzed factors: high electrical performance is obtained in the high level of factor (A) and (C) (a,c) and the middle level of factor (C).





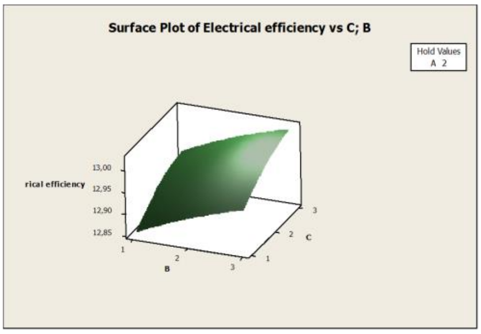


Figure 09: Surface plots for thermal efficiency

Figure 10, shows the surface plots for the thermal performance of CPV panels as a function of analysed factors: high thermal performance is obtained in high level of factor (A) and (B) (a,c) and low level of factor (C).

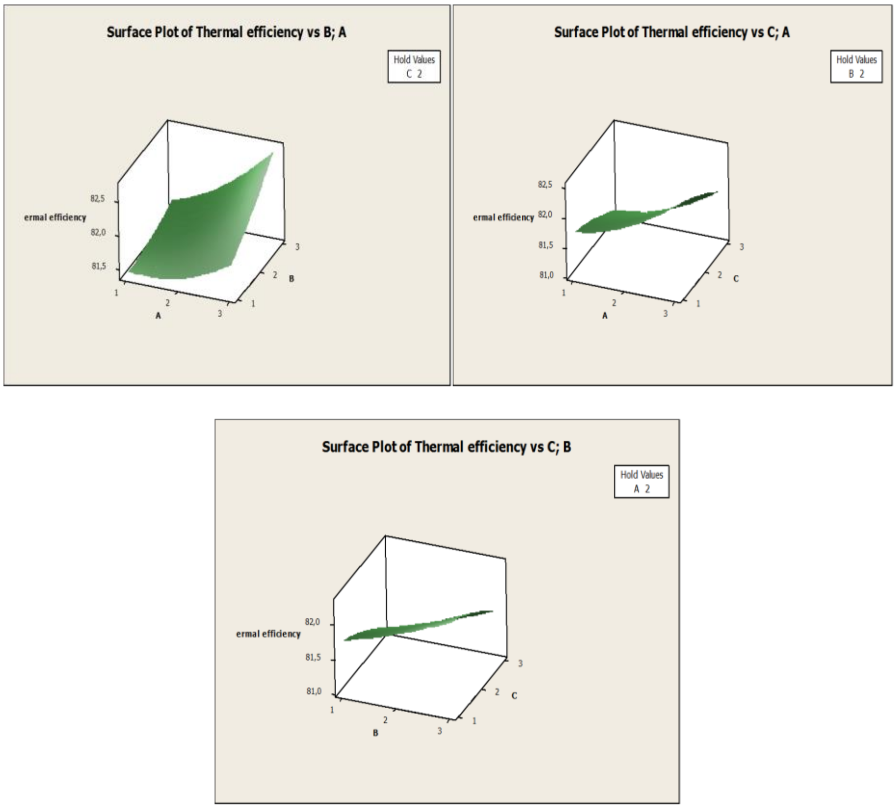


Figure 10: Surface plots for thermal efficiency

6. Conclusion

In conclusion, our study focused on the optimization of CPVT systems with the aim of improving their efficiency, reliability, and durability. By enhancing the performance of CPVT systems, we can make renewable energy production more economically viable, thereby reducing costs and shortening the payback period. Furthermore, the optimization of CPVT systems contributes to the reduction of carbon emissions by replacing the use of fossil fuels in various industrial and domestic applications.

Our investigation specifically examined the impact of three key parameters: the length of fresnel mirrors (A), the angle between the PV panel and the mirrors (B), and the thickness of the glass cover (C). Through the utilization of finite element modeling and statistical analysis techniques such as Design of Experiments (DOE) and Analysis of Variance (ANOVA), we identified the most significant factors affecting the system's efficiency. Additionally, the response surface methodology (RSM) implemented in the Minitab software allowed us to optimize these parameters and determine their optimal values.

Our results demonstrated that the chosen parameters have a substantial influence on the performance of CPVT systems. By adjusting these factors to their optimal values, we achieved remarkable improvements in the system's efficiency. Specifically, our optimized CPVT system attained an electrical efficiency of 13.14% and a thermal efficiency of 82.72%, Soan overall efficiency of 95.86%.

This study adds valuable insights to the existing literature by addressing the lack of research on the selected parameters. The findings highlight the importance of considering these factors in the design and optimization of CPVT systems. Future research can build upon our work by exploring additional parameters and investigating the long-term performance and reliability of optimized CPVT systems.

Overall, our study contributes to the advancement of CPVT technology and provides a foundation for the development of more efficient and sustainable energy solutions.

Nomenclature

A_{fc} *cross-sectional area of the inlet flow channel (m 2)*

C_p *specific heat capacity at constant pressure (J kg -1 K -1)*

C_{pw} *specific heat capacity of water (J kg -1 K -1)*

D_i *inner diameter, m*

E_c *total solar energy absorbed into the cell, W*

E_{el} *electrical energy, W*

E_{th} *thermal energy extracted by water, W*

mass flow rate, kg/s

T_c *temperature of PV cell*

T_{in} water inlet temperature, o C

T_{out} water outlet temperature, o C

T_{ref} reference cell temperature, o C

U_0 inlet water velocity, m/s

ANOVA analysis of variance

DOE Design of Experiments Method

RSM Response surface methodology

FEM Finite Element Method

$ß_{ref}$ temperature coefficient at reference cell temperature

ρ density of the water, kg/m 3

η_{Tref} PV cell electrical efficiency at reference temperature

η_{th} thermal efficiency

η_{el} electrical efficiency

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Data Availability Statement:

In my work, I have not used raw data, but instead, the analysis and calculations are based on publicly available information and published sources. As such, there are no specific datasets to be made available. However, I included a clear description of the sources and methods used for the calculations in the manuscript to ensure transparency and reproducibility.

Competing Interest Statement:

Regarding competing interests, I have no financial or non-financial conflicts of interest to disclose that could influence the results or interpretations of this study. The research was conducted impartially and without any external influences that could compromise its objectivity.