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RESEARCH ARTICLE

Enhancing Photovoltaic Thermal System Efficiency Through Geometric Optimization and Intelligent Fuzzy Logic Based Management

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ABSTRACT The growing demand for sustainable and efficient energy systems has intensified research into improving the performance of photovoltaic thermal (PVT) technologies. This study aims to enhance the electrical and thermal efficiency of PVT systems by integrating material design modifications with intelligent control strategies. A novel methodology is proposed, which involves reducing the thickness of the tedlar layer from 5 mm to 1 mm to improve heat dissipation, alongside the implementation of an adaptive fuzzy logic control (AFLC) system to dynamically regulate the cooling flow rate based on environmental conditions. The results show a notable improvement in system performance, with electrical efficiency increasing from 11.81% to 13.81%, thermal efficiency rising from 27% to 81%, and electrical power output improving from 243.8 W to 271 W under controlled cooling conditions. These findings demonstrate that the proposed integrated approach, named GO-AFLC, effectively maximizes the energy extraction from PVT systems. The combination of passive (material optimization) and active (intelligent control) strategies offers a promising pathway for advancing the performance and sustainability of hybrid solar energy systems.

INDEX TERMS PVT collector, cells temperature, fuzzy logic control, electrical and thermal efficiency, cooling flow rate, electrical power.

I. INTRODUCTION

Photovoltaic thermal systems represent a key innovation in solar technology, playing a vital role in the ongoing global transition toward sustainable and clean energy solutions. As the demand for renewable energy sources such as solar, wind, geothermal, and hydroelectric power continues to rise, PVT systems offer a unique advantage by integrating photovoltaic (PV) panels with thermal collectors into a single unit, enabling the simultaneous generation of electricity and heat [1], [2]. Among the various types, air-based PVT collectors are particularly popular due to their straightforward design and cost effectiveness [3]. However, the overall performance of PVT systems is strongly influenced by their design parameters [4], leading to a growing interest in advanced modeling and hybrid configurations to optimize efficiency.

Likewise, several investigations have examined the impact of PVT design on electrical and thermal performance. Experimental and numerical analyses have been conducted to explore these aspects [5]. Collector geometry, in particular, plays a crucial role in influencing PVT efficiency [6]. Moreover, a numerical and experimental study evaluating the performance of hybrid air type PVT collectors is presented in [7]. Additionally, [8] demonstrates how design variations significantly affect the thermoelectric behavior of air cooled PVT collectors. To enhance output efficiency, researchers have focused on optimizing operating and design

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parameters [9], [10]. Key factors include the air mass flow rate [11] and the overall geometry of the system [12]. For example, integrating fins in the collector design improves both cooling performance and heat recovery [4].

In addition, servals studies have explored both passive and active optimization strategies. Passive strategies include geometric modifications which facilitate better heat dissipation [9]. On the other hand, active strategies focus on intelligent control systems capable of adjusting operational parameters in real time. However, despite converting sunlight into electricity, conventional PV panels are far from 100% efficient [13]. A large portion of solar energy is lost as heat, which raises panel temperatures and leads to a reduction in electrical efficiency [14]. In hot climates, temperatures may reach up to 80°C [15], necessitating efficient thermal management to sustain performance levels. In response, several thermal regulation strategies have been studied. For instance, [16] highlights the advantages of uniform cooling over nonuniform cooling [17]. Phase change materials (PCM) are extensively reviewed for their ability to enhance thermal regulation and electrical efficiency [18], [19]. Other approaches include ground coupled cooling systems [20], as well as passive and active techniques [21], with global overviews provided in [22]. Furthermore, since solar irradiance, ambient temperature, and system load fluctuate throughout the day, maintaining optimal cooling is challenging. Fuzzy logic control (FLC) offers an intelligent solution for real time adjustment of cooling parameters [23], [24], especially when environmental data are used as input variables. This adaptability prevents under or overcooling, thus maintaining system efficiency [25].

Moreover, despite these advancements, challenges remain in achieving optimal PVT system efficiency under varying environmental conditions. Accordingly, researchers have explored advanced materials, optimized geometries [26], and intelligent algorithms [27]. A variable air volume control algorithm applied to a single body PVT system was investigated in a combined numerical and experimental study. Additionally, the use of genetic algorithm fuzzy system (GA-FS) techniques to optimize glazed PVT systems has been reported in [28]. Material configuration also plays a role in thermal management. Reducing the thickness of components such as the tedlar layer has shown improvements in heat dissipation and system efficiency [29]. In the same way, adaptive fuzzy logic controllers, including fuzzy neural networks, have been investigated for real time temperature control [30]. Numerous studies have demonstrated the effectiveness of FLCs for dynamic thermal regulation in PVT systems [31], including integration with ground source heat pumps [32], Autoregressive Moving Average using an external Input (ARMAX) type system modeling [33], and water based collectors [34]. Reference [35] further illustrates improvements in reverse osmosis desalination systems powered by PVT and regulated by fuzzy logic controllers.

This study proposes a combined optimization approach to enhance PVT system performance by integrating geometric design improvements with adaptive fuzzy logic control (AFLC). The passive component involves reducing the tedlar layer thickness from 5 mm to 1 mm, thereby improving thermal conductivity and reducing cell temperature. The active component utilizes a fuzzy logic controller to dynamically regulate the cooling airflow based on sensor data, such as solar irradiance, ambient temperature, and module temperature. The proposed methodology is validated through numerical simulations using a previously developed model [14]. The proposed GO-AFLC supports the goals of sustainable energy systems and smart city development by improving energy efficiency and adaptability. The main contributions of this work are:

- Geometric Optimization (GO): Reduction of tedlar layer thickness to enhance heat dissipation.
- Adaptive Fuzzy Logic Control (AFLC): Real time regulation of cooling flow rate to maintain optimal PV cell temperature.

This paper is structured as follows. Section II covers the methodology and control approach, Section III presents the modeling of the global system, and Section IV introduces the proposed adaptive fuzzy logic control strategy. In Section V we discusses the obtained results and finally, Section VI, concludes the paper and highlights directions for future work.

II. METHODOLOGY AND CONTROL APPROACH

A. IMPROVEMENT OF PVT DESIGN

With respect to the works [36] and [37], the global system is modified with a new geometric design that uses several 20 equidistant fins (see Figure 1). Moreover, the thickness of the tedlar was modified to enhance the electrical and thermal system efficiency. The investigated system exhibits an air duct channel with a thickness of d=0.05 m, a width of b=0.98 m, and a length of a=1.65 m. The air duct channel contains 20 fin absorbers (the thickness of each fin is about 2 cm). The geometric design of PVT systems plays a crucial role in power generation. Extensive research has demonstrated that different geometric configurations significantly impact PVT system performance [37]. It has been concluded that the geometry of the channels and the flow channel configurations at the back of the PV module are the most critical factors for enhancing the heat transfer rate [38]. According to other studies, overall efficiency can be improved by using different geometries for PVT collectors. In this context, [39] used a hybrid PVT solar collector with a novel aluminum heat exchanger with a 94-channel configuration including various fins to improve overall efficiency. The thicknesses of the glass, the silicon solar cells, and the insulation layer are 4 mm, 0.3 mm, and 50 mm, respectively. To optimize the PVT performance, the tedlar thickness has varied between 1mm and 5 mm. The experimental design, data collection, and analysis procedures

TABLE 1. The specifications of PVT air collector of figure 2.

Dimensions	Parameters	Values
Rated Power	P_{mpp}	280
Open Circuit Voltage	V_{oc}	38.7
Short Circuit Current	I_{sc}	8.98
Max Power Current	I_{mpp}	8.52
Max Power Voltage	V_{mpp}	32.8

are illustrated in Appendix. The specifications of the PVT air collector are detailed in Table 1.

B. SMART CONTROL OF COOLING PVT SYSTEM

In this context, fuzzy logic control (FLC) offers a robust and flexible solution for managing the cooling flow rate in PVT systems. Fuzzy logic, known for its ability to handle uncertainty and non-linearity of the system, mimics human reasoning by using a set of rules based on linguistic terms rather than precise mathematical models. This makes it particularly well suited for controlling complex systems like PVT, where the relationships between variables are often difficult to model accurately. By adjusting the cooling flow rate in real time, fuzzy logic controllers can maintain the PV cells at their optimal operating temperature, thereby enhancing both electrical and thermal efficiency. The proposed adaptive fuzzy logic control (AFLC) enhances the traditional fuzzy logic controller by continuously adjusting its rules or membership functions based on changes in environmental inputs. This ensures that the cooling flow rate is optimized for varying conditions, such as solar radiation, PV cell temperature, and ambient temperature. This intelligent approach not only prevents system overheating but also maximizes energy output, making it crucial technology for high performance PVT systems in smart cities. Figure 1 illustrates the various components of the optimization approach for the PVT collector system.

Temperatures fluctuations affect both the electrical performance (through the PV cells) and thermal performance (by capturing and managing heat) of the PVT system. Over heating of PV cells can lead to a significant drop in electrical efficiency, while effective thermal management can enhance the total energy captured. Therefore, understanding and accurately modeling each temperature within the system allows for precise control and maximization of energy conversion. Furthermore, advanced control strategies, such as fuzzy logic or adaptive control systems, can be employed to dynamically adjust the cooling mechanism, ensuring optimal operation under varying environmental conditions. By implementing this controller in a simulation environment MATLAB/Simulink, we were able to validate its effectiveness and study the system's dynamic behavior under different operational scenarios.

This proposed approach contributes to the optimization of photovoltaic thermal systems by focusing on the geometric design adjustment of the tedlar layer thickness and intelligent thermal management through a fuzzy logic control strategy to regulate cooling flow, all aimed at enhancing overall system performance.

III. PVT SYSTEM MODEL

A. DESCRIPTION OF THE ACTUAL PVT SYSTEM UNDER INVESTIGATION

In this research, a 5BB 60-cell polycrystalline module (model IF-P280-60) within a hybrid PVT collector is employed [14]. This collector was tested with a resistive load of 4 ohm. Typically, a hybrid module comprises five layers: a protective glass layer, photovoltaic cells, a tedlar protective layer beneath the photovoltaic cells, tubes or air gaps that surround the collector with heat transfer fluid to convey the generated thermal energy, and insulation to prevent heat loss from the sides and rear of the hybrid solar collector. The preliminary configuration of the PVT system consists of 20 fins with a tedlar thickness of 5 mm. The schematic representation of the PVT system is shown in Figure 2.

B. MODEL AND PERFORMANCE OF THE PVT SYSTEM

1) THERMAL MODEL

The thermal model used in this study for solar PV modules is originally developed by [26] and optimized in [14]. The proposed system has been modeled and validated in the MATLAB R2022b environment based on a meteorological database of real measurements [14]. It included measurements of solar radiation, wind speed, and ambient temperature. The mathematical formulation assumed that the energy transfer was quasi constant. Other hypotheses were the following [14]:

- The airflow velocity along the collector is not affected by duct geometry.
- The temperature gradient within each layer is only in the airflow direction.
- The physical properties of materials remain constant.
- A uniform heat transfer coefficient (U_{fin}) is applied across the entire surface of the fins, assuming that the fin absorbers material is homogeneous and isotropic.
- The junction temperature of the fin absorber is assumed to be equal to the temperature of the fins at the bottom and the top.

The principle of energy conservation is used to anticipate temperatures within a system and determine its electrical and thermal properties. To this end, an energy balance equation can be applied to each component of the hybrid collector [14]. By analyzing the flow rate, the temperatures can be predicted, and the expected electrical and thermal characteristics of the system verified. It should be noted that the specific equations used in the PVT model calculations depend on the design and unique characteristics of the system. The temperature fluctuations for individual layers of the hybrid collector were analyzed by solving the following equations and utilizing the fourth order Runge-Kutta (RK4) method. The design parameters of each layer of the hybrid PVT air collector are summarized in Tables 1, 4, 5, 6, 7 and 8, in the Appendix.

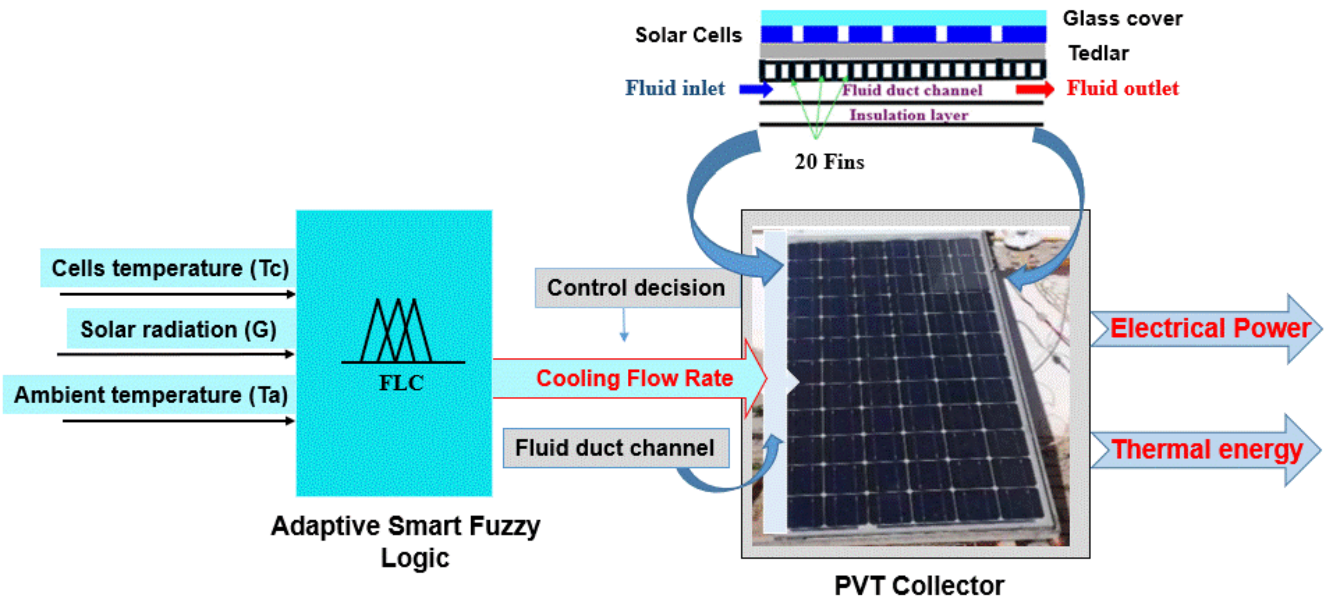


FIGURE 1. Optimization approach for the PVT system.

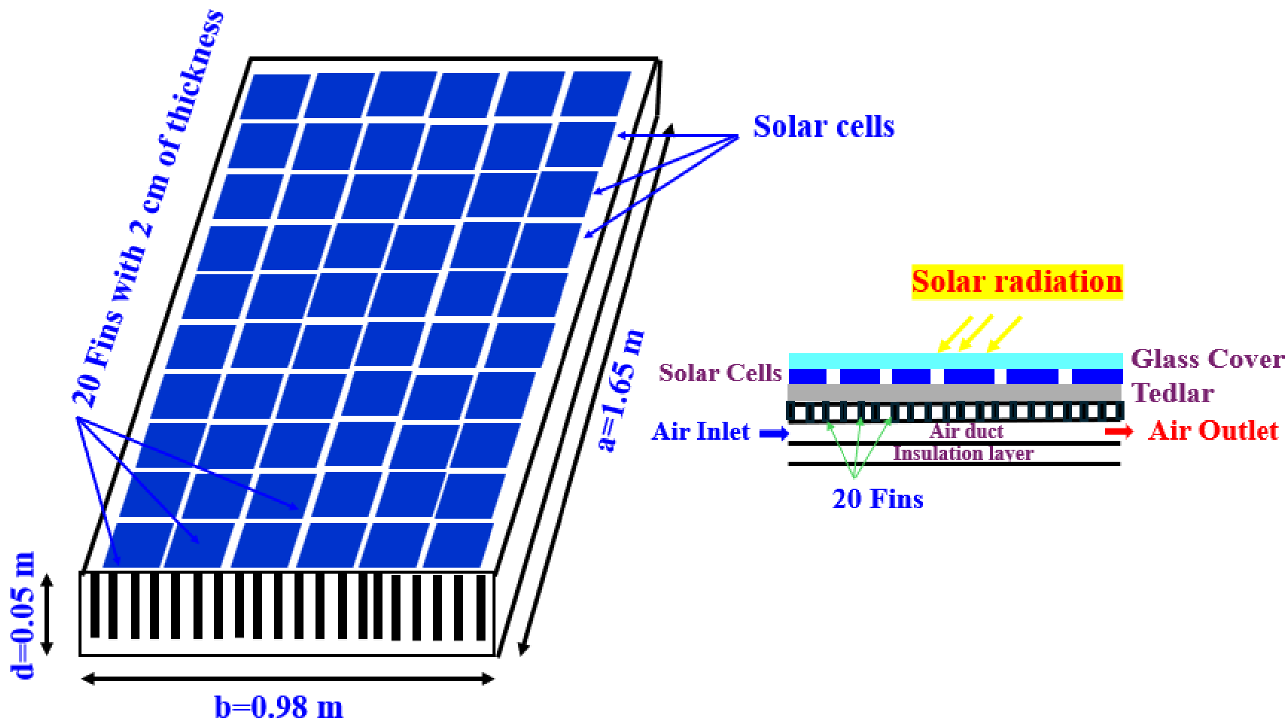


FIGURE 2. The schematic representation of the hybrid PVT air collector system with 20 fins absorbers.

The differential energy balance equations of each layer of the system are expressed as follows: (see nomenclature for units and values of each parameter). The PVT system involves multiple layers (glass cover, PV cells, tedlar and insolation) and a cooling mechanism that extracts excess heat using a fluid. The thermal behavior of the system can be represented by energy balance equations that account for heat transfer between the different layers, the surrounding environment, and the cooling system. The glass cover of the PV module plays a significant role in both heat retention and solar energy transmission to the PV cells. The glass temperature (Tg) is influenced by factors such as:

- Solar radiation (G).
- Ambient temperature (Ta).
- Convective heat transfer between the glass and the surrounding air.
- Radiative heat exchange with the environment.

The energy balance equation for the glass cover is given by [14]:

$$M_g C_g \frac{dT_g}{dt} = A \cdot \Big(\alpha_g G + h_{\text{ra},g\text{-}sky}(T_{\text{sky}} - T_g) + h_{\text{cv},a\text{-}g}(T_a - T_g) - h_{\text{cd},g\text{-}c}(T_g - T_c)\Big) \tag{1}$$

where, α_g is the absorption coefficient of the glass, A is the surface area of the PVT air collector [m^2], and G is the solar irradiance [W/m^2]. The subscripts 'ra', 'cv', and 'cd' refer to radiative, convective, and conductive heat transfer, respectively, while 'g', 'a', and 'c' denote glass, ambient air, and solar cell.

M_g, C_g, and T_g represent the mass [kg], specific heat capacity [$\text{J/(kg} \cdot \text{K)}$], and temperature [°C] of the glass, respectively.

The heat transfer parameters are defined as follows: $h_{\text{ra},g\text{-}sky}$ is the radiative heat transfer coefficient between the glass cover and the sky [$\text{W/(m}^2 \cdot \text{K)}$]; $h_{\text{cv},a\text{-}g}$ is the convective heat transfer coefficient between the glass cover and the ambient air; and $h_{\text{cd},g\text{-}c}$ is the conductive heat transfer coefficient between the glass cover and the solar cell.

The electrical efficiency of the PVT system is directly linked to the PV cell temperature (T_c). A rise in T_c reduces the PV module's output voltage, decreasing overall electrical power generation. In the presented model, the interactions between individual PV cells within a panel are accounted for by representing the entire panel as a single representative cell. The model inherently captures the mutual interactions between adjacent cells, ensuring their influence is reflected in the overall performance. The energy balance equation for the PV cells is given by [14]:

$$M_c C_c \frac{dT_c}{dt} = A \cdot \Big(\tau_g \alpha_c G \cdot F + h_{\text{cd},g\text{-}c}(T_g - T_c) + h_{\text{cd},c\text{-}ted}(T_c - T_{\text{ted}})\Big) - P_{\text{el}} \tag{2}$$

Here, α_c is the absorption coefficient of the solar cell, τ_g is the transmittance of the glass cover, and F is the packing factor (typically 0.83). The subscript 'ted' refers to the tedlar layer. The term $h_{\text{cd},c\text{-}ted}$ represents the conductive heat transfer coefficient between the PV cell layer and the tedlar, while P_{el} denotes the electrical power generated by the PV cells [W].

The electrical power output of the PVT air collector is defined as follows [22]:

$$P_{\text{el}} = \eta_{\text{el}} \cdot A \cdot G \tag{3}$$

With, η_{el} denotes the electrical efficiency of the PVT system.

The variation in the energy balance of the tedlar layer is expressed and calculated as follows [14]:

$$M_{\text{ted}} C_{\text{ted}} \frac{dT_{\text{ted}}}{dt} = A \cdot \Big(\tau_c \tau_g \alpha_{\text{ted}} G \cdot F + \tau_g \alpha_{\text{ted}} G(1-F) + h_{\text{cd},c\text{-}ted}(T_c - T_{\text{ted}}) - h_{\text{cv},f\text{-}ted}(T_{\text{ted}} - T_f) - h_{\text{ra},i\text{-}ted}(T_{\text{ted}} - T_i)\Big) \tag{4}$$

Here, α_{ted} is the absorption coefficient of the tedlar, and τ_c is the transmittance of the solar cell layer. The term $h_{\text{cv},f\text{-}ted}$ denotes the convective heat transfer coefficient between the fluid and the tedlar layer [$\text{W/(m}^2 \cdot \text{K)}$], while $h_{\text{ra},i\text{-}ted}$ represents the radiative heat transfer coefficient between the tedlar and the insulation layer [$\text{W/(m}^2 \cdot \text{K)}$].

The fluid temperature (T_f) determines the efficiency of the cooling process and is vital for maintaining the PV cells temperature within an acceptable range. The cooling fluid absorbs heat from the PV cells and the tedlar, and its temperature evolution is modeled as [14]:

$$\sigma_{\text{f}} v_{\text{f}} C_{\text{f}} \frac{dT_{\text{f}}}{dt} = A \cdot \Big(h_{\text{cv},f\text{-}ted}(T_{\text{ted}} - T_{\text{f}}) + U_{\text{fin}}(T_{\text{ted}} - T_{\text{f}}) - h_{\text{cv},f\text{-}i}(T_{\text{f}} - T_{\text{i}})\Big) - P_{\text{th}} \tag{5}$$

With, U_{fin} represents the overall heat transfer coefficient of the finned surface [$\text{W/(m}^2 \cdot \text{K)}$], and T_{f} denotes the temperature of the fluid inside the duct channel, corresponding to the temperature difference between the outlet and inlet air. The term $h_{\text{cv},f\text{-}i}$ is the convective heat transfer coefficient between the fluid and the insulation layer. The subscripts 'f' and 'i' refer to the fluid and the insulation layer, respectively.

The parameters σ_{f}, v_{f}, and C_{f} represent the density [kg/m^3], volume [m^3], and specific heat capacity [$\text{J/(kg} \cdot \text{K)}$] of the fluid, respectively.

The thermal power emitted by the system is given by the following relationship [14]:

$$P_{\text{th}} = m_{\text{f}} \cdot C_{\text{f}} \left(T_{\text{f,out}} - T_{\text{f,in}}\right) \tag{6}$$

where m_{f} is the mass flow rate [$\text{kg} \cdot \text{s}^{-1}$], $T_{\text{f,in}}$ is the inlet air temperature, and $T_{\text{f,out}}$ is the outlet air temperature.

The energy balance equation for the insulation layer is computed by using the following equation [14]:

$$M_i C_i \frac{dT_i}{dt} = A \cdot \Big(h_{\text{ra},i\text{-}ted}(T_i - T_{\text{ted}}) - h_{\text{cv},i\text{-}a}(T_i - T_a) - h_{\text{ra},gr\text{-}i}(T_i - T_{gr}) - h_{\text{cv},f\text{-}i}(T_i - T_f)\Big) \tag{7}$$

With, $h_{\text{cv},i\text{-}a}$ is the convective heat transfer coefficient between the insulation layer and the ambient, while $h_{\text{ra},gr\text{-}i}$ denotes the radiative heat transfer coefficient between the ground and the insulation layer.

2) PERFORMANCE MODELING

In this study, the calculations of the electrical and thermal performance provide a thorough evaluation of the PVT hybrid collector model. To improve the performance of solar cells for future applications such as energy sources, this study proposes to optimize the efficiency of those kinds of sources by varying some internal parameters such as the tedlar thickness. For PVT systems, the improvement of the solar cells efficiency often includes maximizing the electrical output (photovoltaic efficiency) and thermal output (thermal efficiency). In addition, the enhancement of both electrical and thermal efficiencies can be made by considering other factors such as cost, durability, and environmental impacts. According to previous works [14], it has been confirmed that both electrical and thermal efficiencies can be maximized by controlling the temperature. Hence, the optimization of the thermal efficiency can be conducted by varying the fluid temperature. This parameter is directly affected by fin absorber design, thickness and number, fluid type, and mass flow rate in the air duct channel. In this case, the following relation links the temperature to the thermal efficiency:

$$\eta_{\mathrm{th}} = \frac{m_{\mathrm{f}} \cdot C_{\mathrm{f}} \left(T_{\mathrm{f,\ out}} - T_{\mathrm{f,\ in}}\right)}{A \cdot G} \cdot 100 \quad (8)$$

In our case, the fins create an obstacle to the air flow. To obtain the actual surface area of the flow area, the surface area of the fins must be excluded from the total surface area of the duct channel (see Figure 2). The relation between the mass flow rate m_{f}, the number of fins N, and the fin thickness l_{fin} is given by the following equation [40]:

$$m_{\mathrm{f}} = A_{\mathrm{f}} \cdot \rho_{\mathrm{air}} \cdot V_{\mathrm{air}} = d \cdot (b - N \cdot l_{\mathrm{fin}}) \cdot \rho_{\mathrm{air}} \cdot V_{\mathrm{air}} \quad (9)$$

where, ρ_{air} denotes the air density [kg/m^3], A_{f} is the cross-sectional area of the airflow [m^2], and V_{air} represents the air velocity [m/s].

However, the electrical efficiency is mainly related to the temperature of the PV cells layer in the hybrid PVT collector system. In this case, the system efficiency is dependent on the PV type, the absorbance coefficient, the glass cover transmittance, the tedlar thickness and other parameters. Therefore, we can assume that electrical efficiency can be defined by the following equation [14]:

$$\eta_{\mathrm{el}} = \eta_{\mathrm{ref}} \left[1 - \beta_{\mathrm{PV}} \left(T_{\mathrm{c}} - T_{\mathrm{c,ref}}\right)\right] + \gamma \cdot \ln\left(\frac{G}{G_{\mathrm{STC}}}\right) \quad (10)$$

where $\eta_{\mathrm{ref}} = 15\%$, β_{PV} is the temperature coefficient of the photovoltaic (PV) module, $T_{\mathrm{c,ref}}$ is the temperature of the solar cells under standard test conditions (STC), and γ is the irradiation-related loss coefficient.

The overall efficiency of the PVT system (η_{overall}) is defined as the sum of the thermal and electrical efficiencies, and is expressed as follows [14]:

$$\eta_{\mathrm{overall}} = \eta_{\mathrm{el}} + \eta_{\mathrm{th}} \quad (11)$$

IV. ADAPTIVE FUZZY LOGIC STRATEGY

The proposed intelligent control method exhibits considerable robustness and adaptability in managing thermal parameters for a nonlinear PVT system. Designing a FLC requires careful selection of criteria, including defining linguistic variables, terms, and rules that govern the system operation. In the proposed PVT control system, this involves identifying the relevant input variables for the FLC, then assigning appropriate linguistic terms each with specific ranges to capture variations in system behavior. These terms and rules enable the controller to effectively interpret input data, adjust the cooling flow rate dynamically, and maintain optimal operating conditions. The Membership functions are used to indicate the degree to which input values correspond to each linguistic term, while the output variables reflect the control ac-tions or decisions made by the FLC. These outputs are expressed through linguistic terms tailored to the specific actuators in the PVT collector system. Lastly, the fuzzy rules define the relationships between input and output variables. The proposed AFLC consists of three main components such as: Fuzzification, rule evaluation, and defuzzification. The fuzzification step involves converting crisp input values into fuzzy sets based on predefined membership functions. The rule evaluation applies a set of fuzzy rules that describe the relationships between inputs and outputs, enabling the system to infer conclusions based on the degree of truth of each rule. Finally, the defuzzification step is transforming the fuzzy output sets back into a single crisp value, providing an actionable control signal for the system. Figure 3 presented the algorithm of proposed fuzzy logic controller steps.

This flexibility makes fuzzy logic particularly suitable for control applications in environments characterized by uncertainty, such as the management of cooling flow rates in PVT systems. By utilizing fuzzy logic, systems can adaptively respond to varying conditions, ensuring optimal performance while maintaining operational efficiency. In this research, FLC models that are fine-tuned to safeguard the Cooling Flow Rate (CFR) levels are proposed.

The proposed fuzzy logic controller was developed based on Mamdani method (see Figure 4). The Mamdani Fuzzy Inference System (FIS) is one of the most widely used fuzzy logic models in control applications. It is based on IF-THEN rules, where both inputs and outputs are represented by fuzzy sets. The fuzzification step is essential for converting crisp inputs into fuzzy values, the rule evaluation method is Min-Max method, and the Centroid method calculates the center of gravity of the fuzzy output from the defuzzification step. In addition, the representation of the membership function of the inputs and outputs based on triangular and trapezoidal format.

The AFLC is employed to regulate the cooling flow rate in a PVT system, ensuring optimal operation by maintaining the PV cell temperature within a desirable range. The controller adapts to the varying environmental conditions (such as solar radiation and ambient temperature) by adjusting the

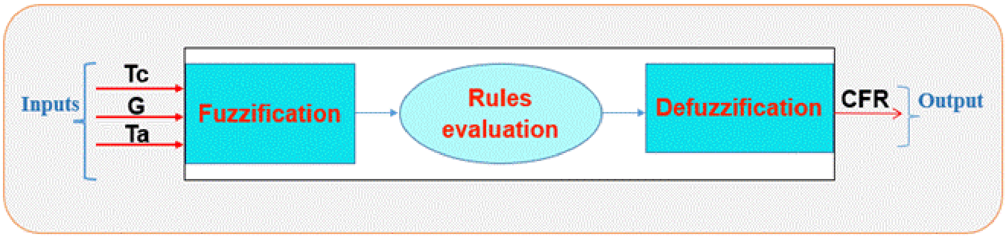


FIGURE 3. Structure of proposed fuzzy logic controller.

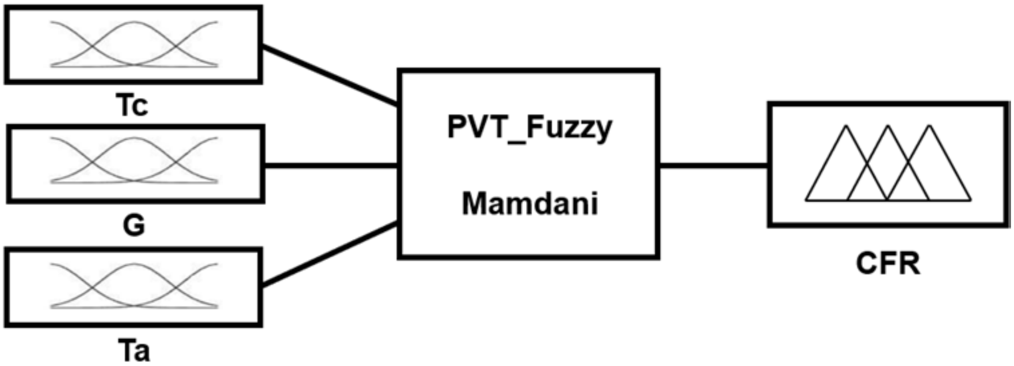


FIGURE 4. Architecture of the fuzzy logic controller.

cooling flow rate, thus improving the electrical and thermal performance of the system. The key control variable is the PV cell temperature (Tc), which strongly influences the electrical efficiency of the system. The AFLC model is based on three input variables for controlling the flow rate of the PVT system and one output variable. The input variables are the cell temperature (Tc), Solar radiation (G) and ambient temperature (Ta). Instead, the output variable is the CFR. Figure 4 presented the architecture of fuzzy logic model.

A. MEMBERSHIP FUNCTIONS OF FUZZY LOGIC CONTROLLER

The membership functions of the input and output variables in the Fuzzy Logic control strategy are shown in Figures 5 and 6, respectively. For example, linguistic terms such as "Low," "Medium," and "High" are used to describe variations in cell temperature (T_c) and solar radiation (G), while "Cold" "Moderate," and "Hot" are used to represent the ambient temperature (T_a).

The output variable, Cooling Flow Rate (CFR), is expressed using linguistic terms such as "Low," "Medium," and "High." "Low" signifies that minimal cooling is required, "Medium" indicates the need for moderate cooling, and "High" represents the necessity for substantial cooling, and illustrated in Figure 6. Fuzzy sets associated with these linguistic variables quantify the degree to which each condition is met.

The ranges of fuzzy sets of inputs variable cell temperature *Tc*, Solar radiation G and ambient temperature *Ta* are defined as follows:

- Tc = Low: [0 to 25]; Medium: [19.5 to 55]; High: [37 to 80].
- G = Low: [0 to 330]; Medium: [268 to 815]; High: [715 to 1100].
- Ta = Cold: [0 to 15]; Moderate: [10 to 23.92]; Hot: [22 to 40].

The output variation of the CFR system is defined with three fuzzy set ranges, as follows: CFR = Low: [0 to 2.99]; Medium: [1.93 to 7.03]; High: [6.12 to 10].

B. FUZZY RULES OF FLC

Inference rules in fuzzy logic for a PVT system are a set of conditional "if-then" statements that define how the system inputs (e.g., cell temperature, solar radiation, and ambient temperature) are used to regulate the output (cooling flow rate). These rules capture expert knowledge about the system's behavior, allowing the fuzzy controller to adaptively adjust the cooling flow rate based on varying environmental and operational conditions.

The implementation of the Fuzzy Logic Controller enhances the efficiency of a Photovoltaic Thermal system, because the controller dynamically manages the system operating conditions to optimize both electrical and thermal performance. The FLC takes multiple inputs, such as solar radiation, ambient temperature, and cells temperature, and processes them using a set of fuzzy rules to determine

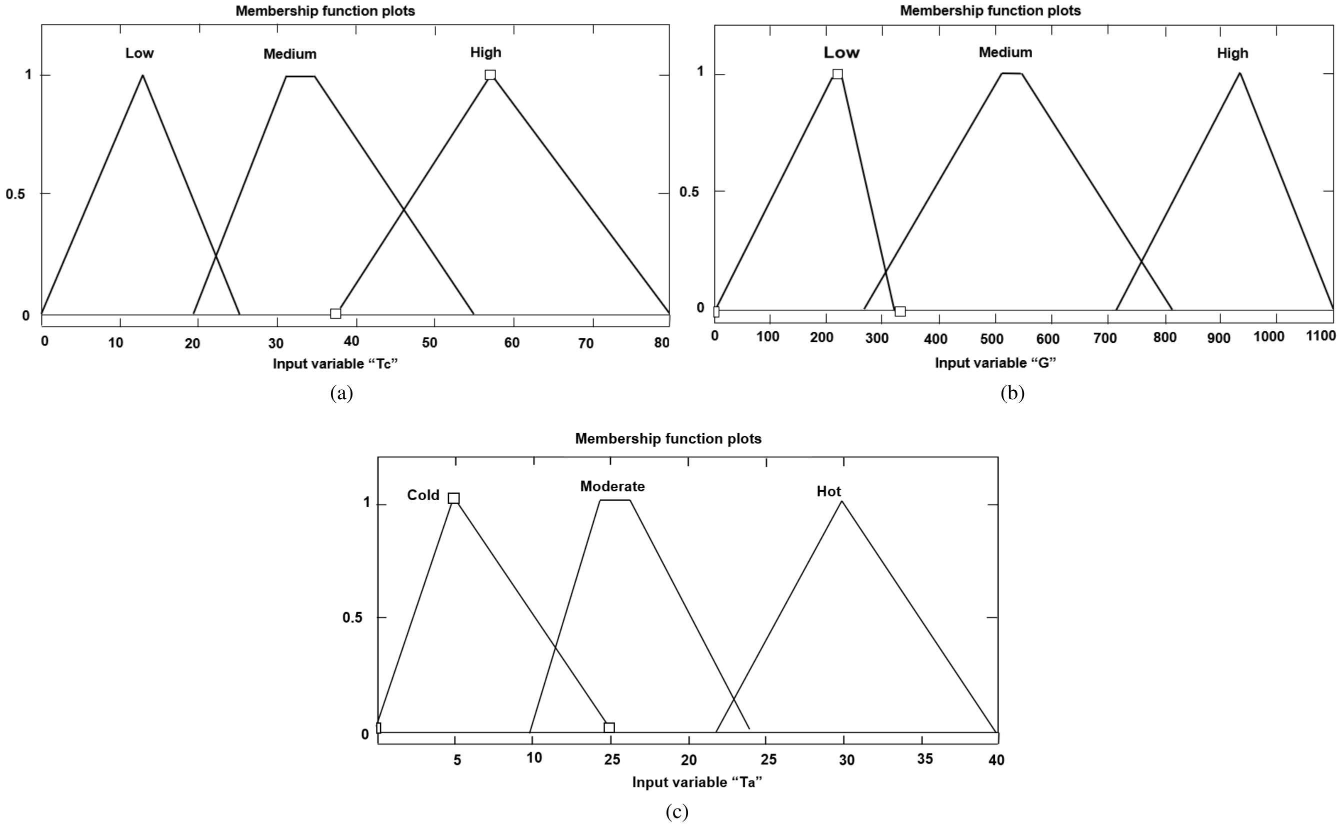


FIGURE 5. **Membership functions of the input variables: (a) membership functions of 'Tc',(b) membership functions of 'G' and (c) membership functions of 'Ta'.**

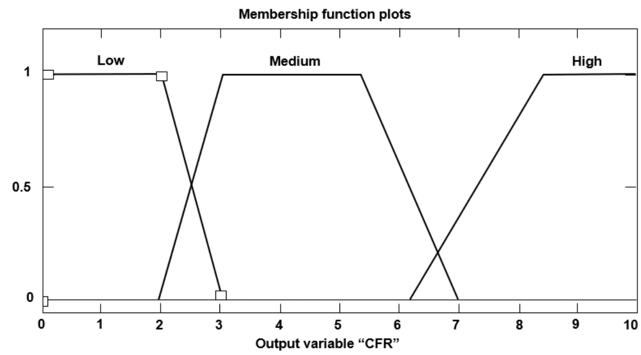


FIGURE 6. **Membership function of the output variable (CFR).**

optimal control actions. Based on these inputs, the FLC adjusts the cooling flow rate CFR to maintain an optimal PV temperature, thereby maximizing electrical efficiency while improving heat extraction for thermal applications. The fuzzy rules, defined by expert knowledge, enable the controller to make real-time, intelligent decisions without requiring a precise mathematical model of the system. The implementation is typically carried out in MATLAB/Simulink, where the fuzzy inference system is designed using appropriate membership functions and rule bases. By continuously adapting to environmental variations, the FLC ensures a balanced trade-off between electricity generation and heat recovery, ultimately improving the overall efficiency and reliability of the PVT system. In addition, the cell temperature is the most affected layer in the PVT system, significantly influencing its overall performance. As the temperature of the PV cells increases, electrical efficiency decreases, while excessive heat can also impact the thermal output. Given this critical factor, we developed an Adaptive Fuzzy Logic Controller (AFLC) to dynamically regulate the flow rate of the cooling fluid entering the PVT system.

The AFLC strategy is built upon predefined inference rules that relate the system input variables. While the rules and membership functions remain fixed, the controller's output continuously adjusts based on variations in the input conditions. In this context, the term "adaptive" refers to the system's ability to respond to changing inputs, rather than incorporating real time learning or self-tuning mechanisms. Similar approaches have been explored in various domains. For example, [41] demonstrated an adaptive fuzzy controller for real-time temperature regulation in a dynamic room, highlighting the effectiveness of rule-based responsiveness. [42] applied a hierarchical adaptive fuzzy control strategy to maintain greenhouse temperatures, showing improved environmental stability under varying external conditions. Reference [43] proposed an adaptive HVAC system based on fuzzy logic that dynamically adjusted to occupant

TABLE 2. Fuzzy rules of inputs and outputs parameters.

Rules	Cells temperature (Tc)	Solar radiation (G)	Ambient temperature (Ta)	Cooling Flow Rate (CFR)
1	Low	Low	Cold	Low
2	Low	Low	Moderate	Low
3	Low	Low	Hot	Low
4	Low	Medium	Cold	Low
5	Low	Medium	Moderate	Low
6	Low	Medium	Hot	Medium
7	Low	High	Cold	Low
8	Low	High	Moderate	Medium
9	Low	High	Hot	Medium
10	Medium	Low	Cold	Low
11	Medium	Low	Moderate	Medium
12	Medium	Low	Hot	Medium
13	Medium	Medium	Cold	Medium
14	Medium	Medium	Moderate	Medium
15	Medium	Medium	Hot	High
16	Medium	High	Cold	Medium
17	Medium	High	Moderate	High
18	Medium	High	Hot	High
19	High	Low	Cold	Medium
20	High	Low	Moderate	Medium
21	High	Low	Hot	High
22	High	Medium	Cold	Medium
23	High	Medium	Moderate	High
24	High	Medium	Hot	High
25	High	High	Cold	High
26	High	High	Moderate	High
27	High	High	Hot	High

needs and ambient variations. Likewise, [44] developed a weather adaptive fuzzy controller to optimize HVAC energy consumption in urban buildings. These studies illustrate that while fuzzy controllers may not involve online learning, their structure can still enable adaptive responses to input variability through well-defined rule sets.

The fuzzy inference rules are used to map the relationship between the input variables (cell temperature, solar radiation, ambient temperature) and the output variable (cooling flow rate). Table 2 reports the fuzzy rules of input and output parameters.

The inference rules, applied to control the CFR under AFLC, are presented in Table 2 and based on the Mamdani rules composition: IF (Tc) is (Low, Medium, High) and (G) is (Low, Medium, High) and (Ta) is (Cold, Moderate, Hot) Then CFR is (Low, Medium, High).

V. RESULTS AND DISCUSSIONS

A. MODEL UNDER INVESTIGATION

The proposed SIMULINK model implements a fuzzy logic-based control strategy to optimize both the thermal and electrical efficiency of a hybrid solar photovoltaic-thermal collector system. Figure 7 illustrates the complete Simulink model of the system developed in this research.

The overall framework consists of four major components. On the left side of the system, the input dataset Block provides real-time and historical measured data collected from the PVT system. These data include critical environmental and operating parameters such as the glass temperature (Tg), cell temperature (Tc), Tedlar temperature (Tted), outlet fluid temperature (Tfout), ambient temperature (Ta), solar irradiance (G), and insulation layer temperature (Ti). The variables (Ta, G and Tc) form the foundation for informed control decisions. At the core of the system is the Fuzzy Logic Controller, which plays a central role in determining the control strategy. It receives a subset of the input parameters primarily ambient temperature (Ta), solar irradiance (G), and cells layer temperature to compute a control signal denoted as CFR (Control Flow Rate). Using a set of fuzzy rules and membership functions, the controller evaluates the current conditions and outputs a suitable CFR to adapt the system's operation dynamically. This intelligent control mechanism allows the system to respond effectively to varying environmental inputs. The PVT System, depicted in the center right section of the diagram, integrates the control signal from the fuzzy logic controller along with the physical inputs (Tg, Tc, Tted, Tfout, Ti, etc.). Under these combined conditions, the PVT panel simultaneously generates thermal energy and electrical power. The influence of the CFR on the system allows fine-tuned management of thermal exchange processes within the panel. Finally, the output metrics, located on the right side of the system, include electrical and thermal efficiencies indicators. Together, these outputs provide a comprehensive assessment of the PVT system's performance. This fuzzy logic-based control framework leverages real-time inputs data to adaptively manage the hybrid PVT system, with the objective of maximizing both thermal and electrical efficiencies. By dynamically adjusting parameters such as flow rate based on environmental conditions, the controller enhances overall system performance in diverse operational scenarios.

In this study, the experimental database consists of real-time measurements collected over a full day, from 5:00 AM to 7:30 PM, representing a complete solar cycle under natural operating conditions. Data was recorded every 60 seconds, resulting in high-resolution time-series data of key climatic and system variables, including ambient temperature, solar radiation, and PV cell temperature. This temporal resolution allows for capturing short-term fluctuations and transient responses of the PVT system. While this one-day dataset offers sufficient variability to evaluate the system's short-term dynamic performance and the responsiveness of the fuzzy logic controller, we acknowledge its limitation in terms of long-term representativeness. Therefore, we have now explicitly stated that future work will include extended data collection campaigns across different seasons to ensure broader validation, along with the implementation of the control strategy in a physical experimental setup.

While the proposed Geometric Optimization with Adaptive Fuzzy Logic Controller has been tested using real time data, the experimental validation presented in this study is limited to a single day (from 5:00 AM to 7:30 PM) under specific weather conditions. Although the high-frequency sampling (every 60 seconds) provides sufficient resolution to evaluate short-term controller performance, the current

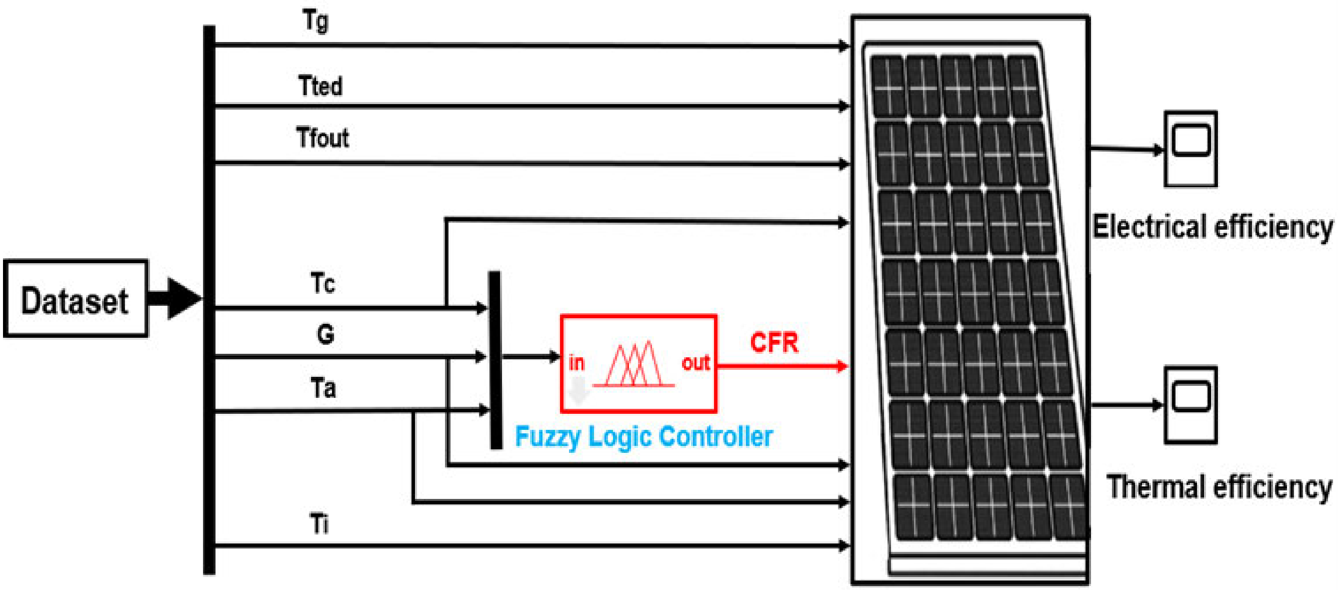


FIGURE 7. SIMULINK model of the overall system.

dataset does not capture long-term or seasonal variations. As part of future work, we aim to extend the experimental campaign over a longer period and deploy the GO-AFLC on a physical prototype. This will facilitate comprehensive validation of the controller's performance, adaptability, and robustness across a range of real-world operating conditions.

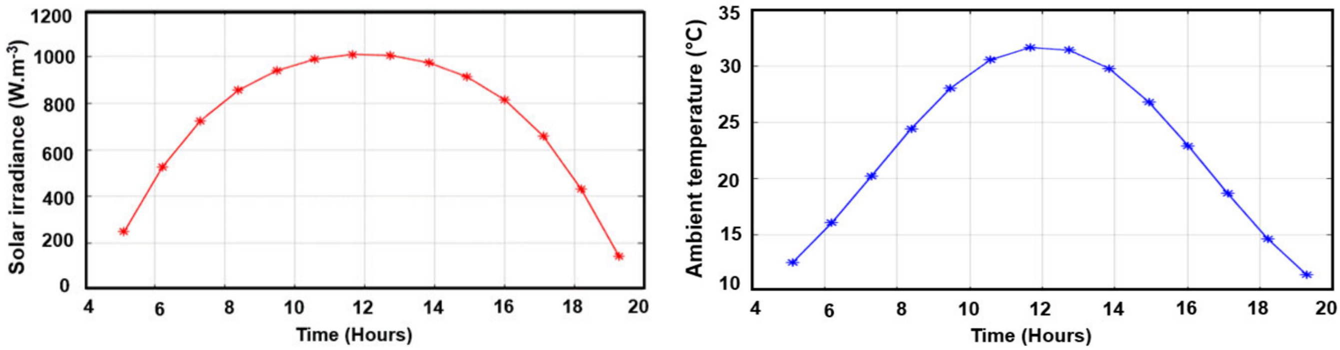
B. PVT SYSTEM OUTCOMES

The outcomes result of the PVT model based on experimental climatic variables, the dynamic model continues the different layers such as the glass as cover layer, the polycrystalline solar cells to govern the generation of the electrical power, and the tedlar layer, which assures the film protection. This section aims to check the effect of heat capacity of the tedlar on the temperature of a PVT system. The air duct channel in the studied structure is used to regulate both the mass flow rate and temperature in the area, with a particular focus on controlling the temperature of the cells. Finally, the insulation layer is used to conserve the fluid temperature in the air channel. The implementation system is validated over a single day, covering both cold and hot periods, from 5 AM to 20 PM. The solar radiation 'G' and ambient temperature variation are presented in Figure 8.

For the studied system, both factors are found to increase versus time until they reach a maximum plateau between 11:30 H and 13:00 H. After that, the solar radiation and temperature decrease rapidly. This maximum affects mainly the environmental temperature that reaches its maximum of 31.69 °C at the same time as solar radiation. To validate the proposed dynamic model of the different layer's temperature, we considered 20 fins absorbers and a tedlar layer of thickness equal to 5 mm. Figure 9 shows the time-domain temperature of the glass, solar cells, tedlar, air fluid and insulation layers' temperatures during the test period.

The curves are carried out by using the Runge-Kutta method and based on the MATLAB software. The results indicate that the solar cells layer exhibits a maximum optimum temperature equal to 71.8°C. This layer absorbs a part of temperature from both the tedlar layer (57.5°C) and the glass cover layer (69.6°C) that is directly disposed to the solar irradiance when is maximum values 1000W/m2. The minimum peak temperature is reported for the insulation layer equal to 32.6°C, which is the farthest layer of solar radiation. Noticeably, the PVT air collector's performance is extremely dependent on the fixed operating factors and conditions. The results show that the cell temperature in the PVT system reaches a high value of 71.8°C compared to other temperature layers. To address this, we propose a geometric optimization of the tedlar thickness to improve the cooling system's performance. Early experimental reports, following multiple tests, have demonstrated that layer thickness directly impacts both electrical and thermal efficiencies, which are key factors in optimizing PVT system operation. The variation in tedlar layer thickness affects the temperature of each layer. Figure 10 illustrates the temperature values of the different components.

Figure 10 exhibits the time-domain temperature for different film thicknesses varying from 1 mm to 5 mm and for glass (a), PV cells (b), tedlar (c), air channel (d) and insulating cells(e). For the glass layer (see Figure 10(a)), an optimum temperature value of 69.6 °C is reached when the tedlar thickness is about 5 mm. This optimum value decreases when the tedlar thickness decreases, until reaching a value of 62 °C for 1 mm of thickness. As illustrated in Figure 10(b), a maximum of 71.8 °C was reached at around



(a) (b)

FIGURE 8. Time-domain solar radiation (a) and environmental temperature (b) during the test day.

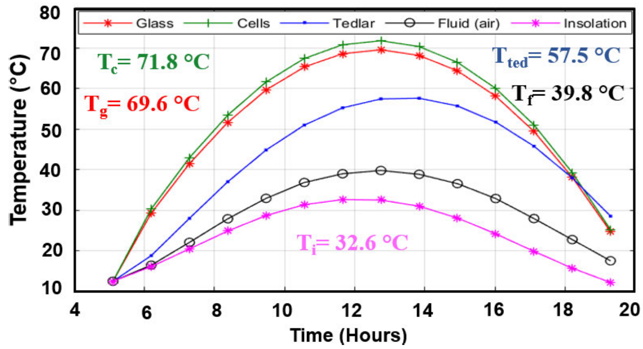


FIGURE 9. Time-domain temperature for the hybrid collector layers, with 20 fins absorber and tedlar thickness of 5 mm.

13:00 H and for a larger thickness tedlar layer of 5 mm. In this case, the temperature decreased by more than T=8 °C, by decreasing the tedlar thickness. At this point, the observed PV cells temperature decreasing can mainly contribute to improving the electrical efficiency of the studied system. For the tedlar layer (Figure 10(c)), the tedlar thickness does not affect its optimal temperature. Therefore, a maximum temperature value of 57.5 °C is reached at around 13:00 H. As shown in Figure 10(d), the maximum air duct channel temperature is found to increase mainly when the tedlar thickness decreases from 39.8°C for 5 mm to 49.5°C for 1mm thickness. Here, the more the temperature increases the more the thermal efficiency of the studied system increases, and therefore the performance enhances. For the insulation layer, the obtained results in Figure 10(e) show the presence of an optimum stable temperature plateau between 11:30 H and 13:00 H. The maximum temperature is found to increase with decreasing the thickness from 32.6 °C for 5 mm of tedlar thickness to 34 °C for 1 mm. According to the previously mentioned results, we can assume that the decreasing of the tedlar thickness improves mainly the efficiency of the PVT air collector. All the studied layers show a maximum temperature around 13:00 H. At this time, solar radiation reaches its peak, resulting in a broad temperature rise observed across all layers. The layers' temperature characteristic of the PVT system based on 1mm of the tedlar thickness is presented in Figure 10.

Compared to the results in Figure 9, where the tedlar thickness is 5 mm, reducing the tedlar thickness does not affect its temperature, which remains at a maximum of 57.5°C. However, it is confirmed that reducing the tedlar thickness significantly impacts the temperatures of the other layers, particularly the cell temperature, which decreases to 63.7°C cooler than in the PVT system with a tedlar thickness of 5 mm.

C. FUZZY LOGIC OUTCOMES

Based on the previous results, the optimal tedlar thickness is determined to be 1 mm, with fluid flowing through the duct channel to cool both the tedlar and PV cell layers. In this context, we propose an intelligent fuzzy logic controller to regulate the cooling flow rate, aiming to reduce the temperature of the PVT cells, thereby improving the system's overall performance. For this reason, controlling the flow rate within the channel directly regulates the temperature of the solar cells, which in turn enhances their electrical efficiency. The simulation results of the cooling flow rate adjusted by the fuzzy logic controller (FLC) are presented in Figure 12. The output control of fuzzy logic based on solar radiation, Temperature ambient and actual cells temperature of the PVT system.

Based on the inference rules illustrated in Table 2, the variation in cooling flow rate to regulate the cell temperature during the test period ranges between 3.7 m^3/s and 7.8 m^3/s. During the cold periods from [5 AM to 7 AM] and [6 PM to 7 PM], when solar radiation and ambient temperatures are low, the cell temperature is also lower. In this case, the fuzzy logic controller produces a Cooling Flow Rate between 3.7 and 6 m^3/s. However, during the hot period, from 7 AM to 5 PM, as the external climatic factors increase, the cell temperature gradually rises. To address this, the fuzzy logic controller adjusts its rules, increasing the flow rate to as high as 7.8 m^3/s.

Based on the comparison of the inference rules of the adaptive fuzzy logic controller, The variation of CFR in

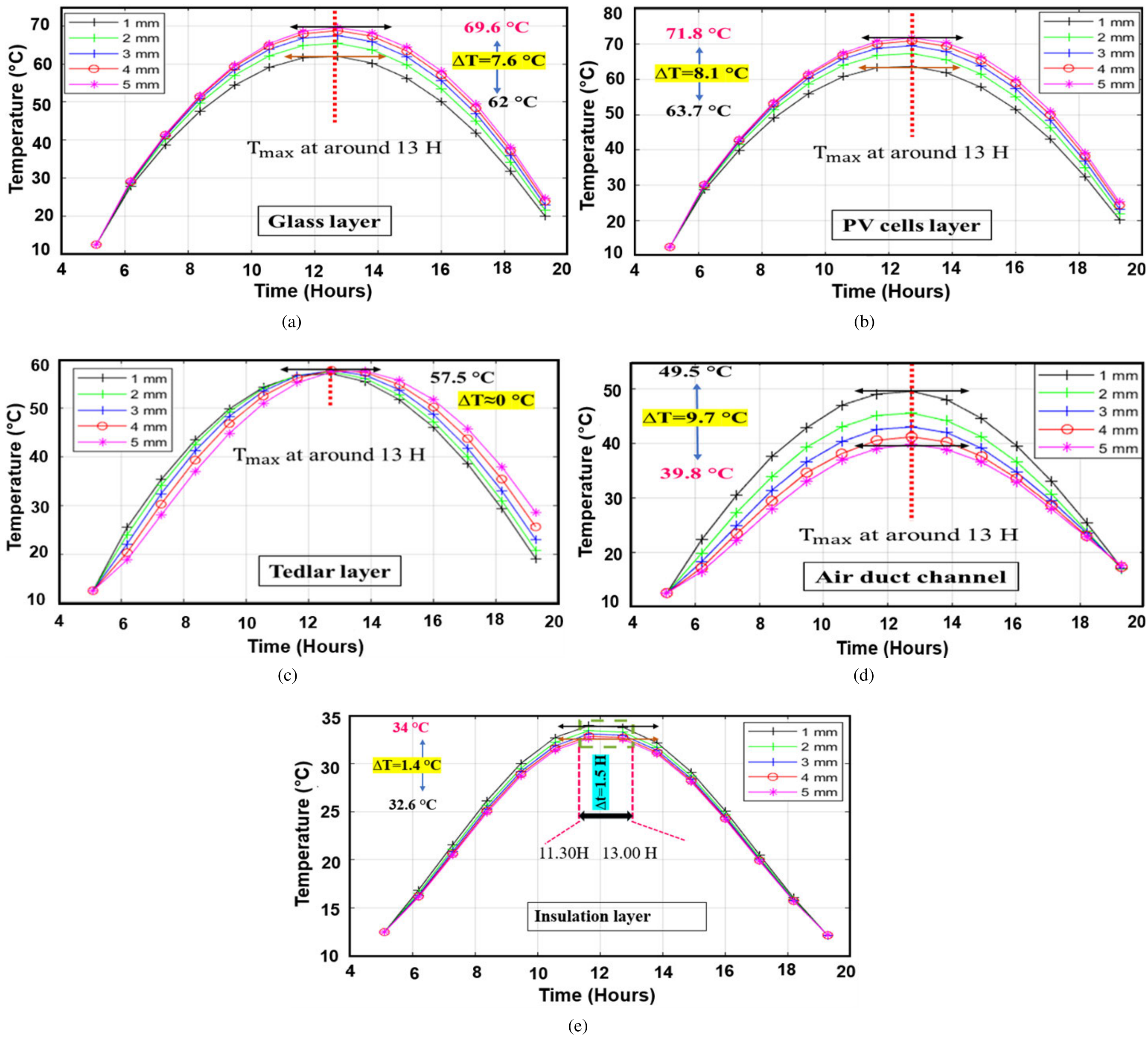


FIGURE 10. Time-domain temperature for one day of different components: (a) glass; (b) PV cells; (c) tedlar; (d) air duct channel; (e) insulation.

relation to the input variables is presented in the fuzzy surface plots as illustrated in Figure 13. Those plots illustrate how CFR dynamically responds to changes in solar radiation (G), ambient temperature (Ta), and PV cell temperature (Tc) based on the fuzzy logic control system.

In Figure 13(a), which represents the relationship between CFR, solar radiation (G), and ambient temperature (Ta), we observe that as G increases from 0 to 1000 W/m^2, the CFR also rises due to higher heat generation in the PV module. Similarly, when Ta increases from 0°C to 40°C, the system reacts by increasing the CFR to ensure efficient cooling. At low values of G around (200 W/m^2) and Ta around (10°C), the CFR remains relatively low, around 0.2-0.4 (m^3/s), as minimal cooling is needed. However, at higher G is around (900 W/m^2) and Ta with a value (40°C), the CFR reaches its peak at 0.9-1.0 (m^3/s), indicating that the controller efficiently responds to prevent overheating. From Figure 13(b), which examines the relationship between CFR, PV cell temperature (Tc), and ambient temperature (Ta), a similar trend is observed. When Tc is low (10°C) and Ta is also low (10°C), CFR remains minimal at around 0.2 (m^3/s), as there is no significant need for cooling. As Tc increases beyond 50°C, the controller adjusts the CFR to higher values, reaching 0.9-1.0 (m^3/s), ensuring that excessive heat is dissipated. The impact of ambient temperature is also significant; for instance, at high Ta equal around (40°C), the CFR increases more rapidly, showing that the fuzzy controller considers combined heating effects to

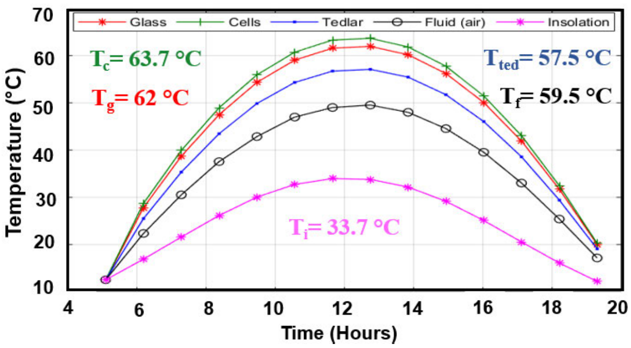


FIGURE 11. The time-domain temperature for the hybrid collector layers for a tedlar thickness of 1 mm.

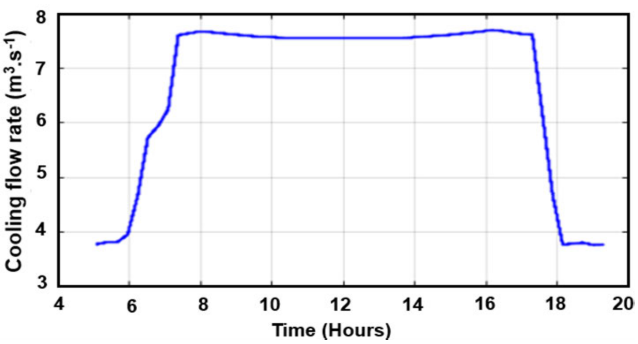


FIGURE 12. Simulation results of the cooling flow rate under FLC.

maintain optimal PVT system performance. The outcomes in the Figure 13(c), which illustrates CFR variations with solar radiation (G) and PV cell temperature (Tc), we see that at low G (100 W/m^2) and low Tc (10°C), the CFR is minimal by (0.2-0.3 units), meaning the cooling requirement is low. However, as G exceeds 800 W/m^2 and Tc surpasses 50°C, CFR sharply increases until (0.9-1.0 m^3/s), demonstrating that the controller effectively adapts the cooling action based on real-time changes in energy input and temperature. The non-linear nature of the fuzzy surface plots confirms that the controller dynamically adjusts CFR in response to environmental variations to optimize both thermal and electrical performance of the PVT system.

The simulation results show that the cooling flow rate increases as the values of solar radiation, cell temperature, and ambient temperature rise. Conversely, the opposite is also true. The outcomes result of the cell temperature control under the adaptive fuzzy logic are presented in Figure 13.

In the first hour of the test period, from 5 AM to 6 AM, the uncontrolled cell temperature (green curve) varies between 20°C and 30°C. During this time, the fuzzy logic controller applies a flow rate of 3.7 m^3/s (see Figure 9), resulting in a 2°C decrease in the controlled cell temperature (red curve). Conversely, at 13H, the uncontrolled cell temperature fluctuates around 63.7°C. At this point, the fuzzy logic controller increases the flow rate to 7.8 m^3/s. Due to this intensive flow rate, the cell temperature decreases significantly by 18.7°C, resulting in a final temperature of 45°C under fuzzy control. The control results demonstrate the effectiveness of the fuzzy logic controller, based on the proposed rules, in reducing cell temperature through the adjustment of the cooling flow rate. This optimization enhances both the electrical and thermal performance of the PVT system. The reduction in cell temperature provides a valuable solution for improving overall system performance. The simulation results of the solar cells temperature under FLC is presented in Figures 14. In the next step, Figures 15 and 16 show the electrical and thermal efficiency of the system with and without fuzzy logic control.

The electrical performance of the PVT system decreases as the cell temperature rises. At 13H, the system experiences a higher cell temperature of 63.7°C (see the green curve in Figure 14), resulting in a low electrical efficiency of approximately 11.81% (blue curve). However, when the cooling system is activated with a flow rate of 7.8 m^3/s (see Figure 12), the system's performance improves by 2%, increasing the efficiency to 13.81% (red curve). The ability to increase electrical efficiency by simply optimizing material thickness and implementing intelligent cooling systems offers a sustainable solution for improving the performance of PVT systems. The increase in electrical performance without the need for additional energy inputs to the system helps reduce overall energy consumption, contributing to a more efficient and sustainable operation.

Regarding thermal efficiency, when the cooling system is activated to manage the cell temperature of the PVT system, thermal energy extraction reaches 54%, compared to the thermal energy without control 27% (blue curve), which shows a decrease in efficiency to around 81% (red curve). These results demonstrate the effectiveness of the cooling system in optimizing both electrical and thermal performance, highlighting the correlation between the two types of energy in the PVT system where obtain an overall efficiency equal to 94.81%. Furthermore, the cooling flow rate controlled by the AFLC provides an effective solution to optimizing the PVT system, reducing energy consumption and increasing the electrical power output. The implementation of a cooling system plays a pivotal role in enhancing electrical power output. By maintaining lower cell temperatures through active cooling, such as adjusting the cooling flow rate with a fuzzy logic controller, the system performance can be significantly improved. In the tested scenario, the electrical power output of the PVT system is analyzed under different conditions: with a tedlar thickness of 5 mm, optimized to 1 mm, and further enhanced the cooling system by the fuzzy logic control. These results are illustrated in Figure 17, highlighting the impact of cooling strategies on electrical power.

The optimization methodology aimed to enhance the performance of the PVT system by reducing the tedlar thickness from 5 mm to 1 mm. After this geometric optimization, we implemented the Adaptive Fuzzy Logic Controller (AFLC) to further regulate the cooling process

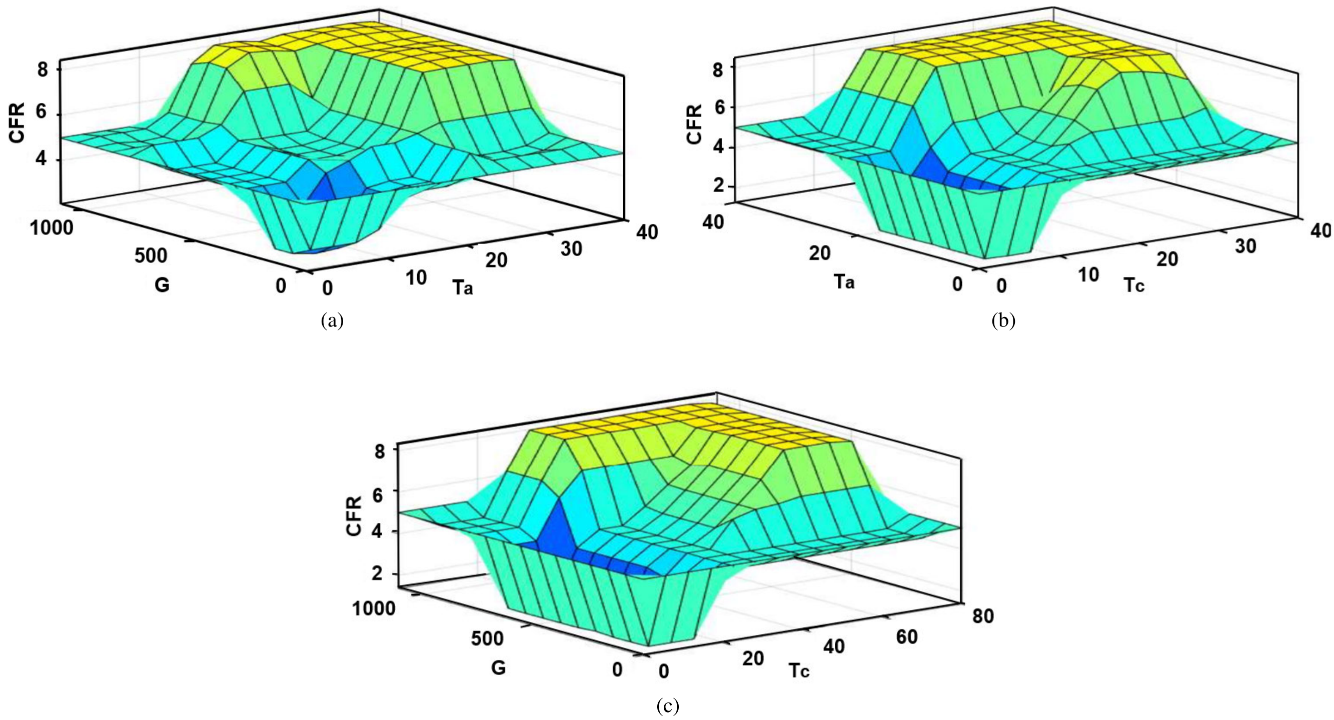


FIGURE 13. Surface evolution of the fuzzy Logic controller.

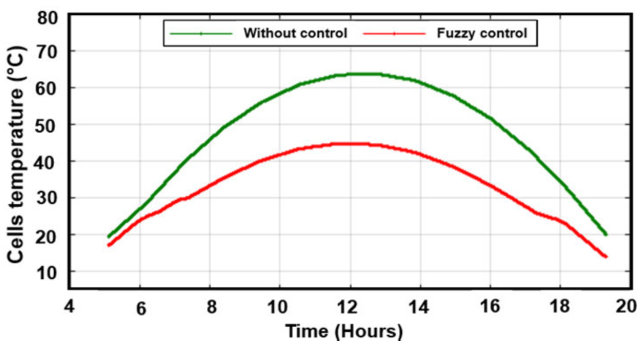


FIGURE 14. Simulation results of the solar cells temperature under FLC.

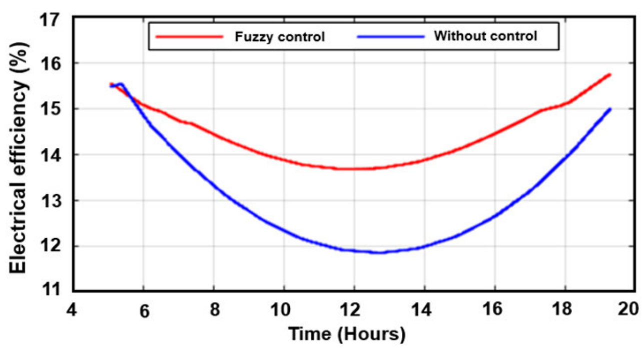


FIGURE 15. Simulation results of the electrical efficiency for PVT collector with FLC.

and improve system efficiency. The Geometric Optimization combined with Adaptive Fuzzy Logic Control (GO-AFLC) method was applied using tedlar layer with a 1 mm thickness, ensuring an optimized thermal management strategy.

The electrical power delivered by the PVT system in the initial phase, with a tedlar thickness of 5 mm, varies between 60 W and 243.8 W at 1 PM (see blue curve). By optimizing the tedlar thickness to 1 mm, the electrical power output increases compared to the 5 mm thickness, reaching around 256.4 W (red curve). Furthermore, when the cooling strategy is implemented to adjust the flow rate through fuzzy logic control the electrical power is further optimized, increasing to 271 W (green curve), due to the effective reduction of the internal temperature within the PVT system. The comparison of these results demonstrates the effectiveness of both passive (material optimization) and active (fuzzy logic-controlled cooling) strategies in enhancing the electrical performance of PVT systems. The increase in electrical power, from 243.8 W with a 5 mm tedlar to 271 W with optimized cooling, shows the significant potential for improving system efficiency through targeted design improvements. Table 3 presents a comparison of our model, which uses the GO-AFLC approach, with recent studies employing other cooling techniques.

Table 3 compares the proposed cooling technique approach GO-AFLC with other available methods. While some systems achieve higher overall efficiencies, the current research attains an overall efficiency of 94.81%.

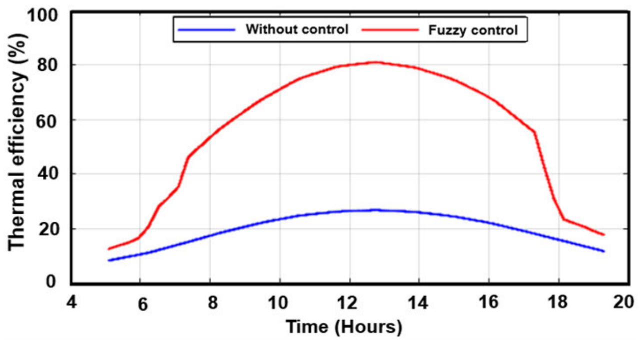


FIGURE 16. Simulation results of the thermal efficiency system under FLC.

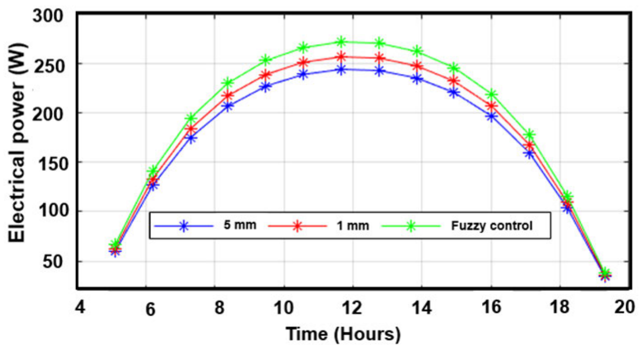


FIGURE 17. Electrical power of PVT system under different approach.

References [14], [50], [51], [52], and [54] utilize nanofluids as a cooling fluid across various cooling techniques. The results of these studies indicate overall efficiencies of 60.61%, 66.5%, 49.88%, 71.85%, and 62.08%, respectively.

References [46], [47], and [49] examine the use of water as a coolant in different cooling techniques. The results of these studies show overall efficiencies of 83.88%, 20.8%, and 61%, respectively. The upper and lower channel cooling technique [48] uses a mixture of water and air as the cooling fluid to achieve an overall efficiency of 85%.

References [45], [53], and [55] investigate the application of air as a coolant in various cooling techniques, reporting overall efficiencies of 66.4%, 49.21%, and 55.09%, respectively. The GO-AFLC approach, which also utilizes air as a cooling fluid, achieves an electrical efficiency of 13.81%, a thermal efficiency of 81%, and an overall efficiency of 94.81%. The results briefly show that our GO-AFLC approach, as a cooling technique in PVT collector systems, is very effective, also compared with other recent cooling techniques in the literature.

The proposed PVT system, enhanced with the GO-AFLC demonstrates strong real world feasibility in terms of cost-effectiveness, scalability, and deployment potential. From a cost perspective, the system is economically attractive, as the adaptive fuzzy logic control can be implemented using low-cost embedded platforms such as Arduino [56], [57], Raspberry Pi [58], or industrial grade microcontrollers [59]. Additionally, the geometric optimization of the fin structure contributes to material savings and increased thermal efficiency, aligning with the techno economic priorities discussed in recent studies [60]. Deployment feasibility is further enhanced by the system's reliance on standard, widely available components such as temperature, solar radiation, and flow rate sensors, along with conventional heat exchanger elements [61]. In terms of scalability, the GO-AFLC framework is flexible and can be applied to a range of PVT system sizes, from small scale residential installations to larger industrial applications. This is made possible by its data driven control approach, which eliminates the need for extensive redesign when scaling up consistent with findings on scalable PVT solutions for diverse environmental conditions [62].

TABLE 3. Comparison of PVT systems efficiencies by using different cooling techniques.

Cooling Technique	Electrical Efficiency (%)	Thermal Efficiency (%)	Overall Efficiency (%)	References
Channels with baffles	13.6	52.8	66.4	[45]
Tubes with twisted tapes	11.88	72	83.88	[46]
Corrugated channel	10.3	10.5	20.8	[47]
Upper and lower channels	13.2	50	85	[48]
Open box with baffles	13	53	61	[49]
Spectral beam splitter	12.5	48.1	60.61	[50]
No solar tracker concentrator	6.5	60	66.5	[51]
Reflector linear and flat mirror	9.1	40.78	49.88	[52]
4 Fins absorber	13.55	35.66	49.21	[53]
No concentrator	13.20	48.88	62.08	[54]
Fin absorbers	13.82	58.03	71.85	[14]
V-groove absorber	12.72	42.37	55.09	[55]
GO- AFLC	13.81	81	94.81	This paper

D. DISCUSSION AND CONTRIBUTIONS

This research makes four important contributions to the optimization of PVT systems, specifically through material thickness adjustment and intelligent thermal management. First, by reducing the tedlar layer thickness from 5 mm to 1 mm, the study shows a significant improvement in thermal and electrical performance. This geometric optimization allows for better heat dissipation, reducing the operating temperature of PV cells and enhancing overall efficiency. Second contribution regards the integration of a fuzzy logic controlled cooling system, which marks a key advancement in real time temperature regulation for PVT systems. The fuzzy logic controller dynamically adjusts the cooling flow rate based on environmental conditions, which maintains lower cell temperature and maximizes the electrical power output. This adaptive control strategy introduces a more intelligent and energy-efficient method for optimizing the system performance. As third point, the proposed solutions help to reduce the energy consumption for cooling by optimizing the flow rate and only using it when necessary. This contribution is crucial for increasing sustainability, operational efficiency, and the cost effectiveness of PVT systems. As last point, the novelty in this research lies in its combined approach GO-AFLC to optimize both passive and active thermal management strategies in PVT systems. These innovations make the PVT system more efficient, sustainable, and capable of generating more power with less energy waste. The combined passive (tedlar thickness) and active (fuzzy logic cooling) approaches introduce a holistic strategy for system optimization, which can be a basis for future developments in this field.

The paper is based on an experimental dataset and the simulation results suggest the goodness of the proposed system modelling. Nevertheless, real world environmental variability and long term material performance need to be studied in a future work. Moreover, the paper is focused on tedlar thickness and fuzzy logic control, without examining other passive or active thermal management strategies, which need an indepth analysis.

VI. CONCLUSION

This research presents a comprehensive approach to enhancing the performance of PVT systems through a combination of geometric design refinements and advanced thermal management techniques. By decreasing the tedlar layer thickness from 5 mm to 1 mm, the system achieves better heat dissipation, leading to lower cells temperature and improved electrical and thermal efficiency. Furthermore, the implementation of a fuzzy logic control strategy for dynamic regulation of the cooling flow rate further enhances system performance by maintaining optimal operating conditions.

The results demonstrate that reducing the cell temperature significantly improves electrical output, with power increasing from 243.8 W to 271 W under controlled cooling conditions. Similarly, thermal efficiency is improved, showing the efficacy of the proposed strategies in balancing both electrical and thermal energy extraction.

This study highlights the significance of both passive (thickness tedlar optimization) and active (intelligent cooling control) methods for optimizing PVT systems. The combination of these approaches GO-AFLC provides a sustainable and effective solution for improving the overall efficiency of PVT systems, reducing energy consumption, and increasing power output.

Future work will explore further refinements in material properties and advanced control systems to further enhance the potential of PVT technologies in renewable energy applications.

APPENDIX

Experimental Design:

This study relies on a thermal model developed in [14], while the electrical efficiency was validated in [36]. The experimental setup was configured as described in [37].

TABLE 4. The baseline parameters for the glass cover layer are used in the simulation. Units in Nomenclature.

Parameters	Symbol	Values
The thickness	λ_g	0.004
The specific heat	C_g	670
The density	σ_g	2200
The thermal conductivity	e_g	0.93
The absorption coefficient	α_g	0.066
The emissivity	ϵ_g	0.88
The transmittance	τ_g	0.95

TABLE 5. The baseline parameters for the solar cell layer used in the simulation. Units in Nomenclature.

Parameters	Symbol	Values
The thickness	λ_c	0.0003
The specific heat	C_c	900
The density	σ_c	2230
The thermal conductivity	e_c	148
The absorption coefficient	α_c	0.9
The emissivity	ϵ_c	0.93
The transmittance	τ_c	0.07

TABLE 6. The baseline parameters for the tedlar layer are used in the simulation. Units in Nomenclature.

Parameters	Symbol	Values
The thickness	λ_{ted}	[0.005 0.001]
The specific heat	C_{ted}	1400
The density	σ_{ted}	1390
The thermal conductivity	e_{ted}	0.33
The absorption coefficient	α_{ted}	0.5
The emissivity	ϵ_{ted}	0.88

The experiment was conducted using a photovoltaic thermal system equipped with an air cooling mechanism to enhance efficiency. The system includes multiple IoT based sensors to monitor key parameters such as solar radiation (G), ambient temperature (Ta), PV cell temperature (Tc), and cooling fluid rate (CFR). The setup was designed to evaluate the performance of the model. Figure 18 below describes the real experimental device.

The experimental setup includes various sensors connected to the CR5000 data logger to ensure accurate monitoring of key parameters. Anemometers are utilized to measure wind speed, providing insights into air circulation and its effect on temperature regulation. A Kipp & Zonen pyranometer is employed to measure solar irradiance with an accuracy of ±5%, ensuring precise assessment of solar energy input. Additionally, thermocouples are integrated to monitor the temperature of the PV cell layer, enabling effective thermal analysis of the system.

Data Collection

The dataset was obtained from real-time measurements recorded over a specific period under varying climatic conditions. Sensors continuously measured solar radiation (W/m^2), temperatures (°C), and fluid flow rate (L/min) at fixed intervals. The collected data was stored in a database for further processing and used as input for the fuzzy logic

FIGURE 18. Real photo of the PVT collector.

TABLE 7. The baseline parameters for insulation layer are used in the simulation. Units in Nomenclature.

Parameters	Symbol	Values
The thickness	λ_i	0.05
The specific heat	C_i	919
The density	σ_i	24
The thermal conductivity	e_i	0.039
The absorption coefficient	α_i	0.066

TABLE 8. The baseline parameters for the fin absorbers used in the simulation. Units in Nomenclature.

Parameters	Symbol	Values
The thickness	λ_{ab}	0.002
The specific heat	C_{ab}	36
The density	σ_{ab}	8000
The thermal conductivity	e_{ab}	410
The absorption coefficient	α_{ab}	0.75
The emissivity	ϵ_{ab}	0.04

TABLE 9. The characteristics of the IoT measurement sensors.

Sensors	Company	Accuracy
Pyranometer	Kipp & Zonen	±5%
Anemometer (PCE-A 420)	PCE instruments	±2 %
Data acquisition (CR5000)	Campbell scientific	±5%

controller (FLC). The characteristics of the sensors are mentioned in Table 9.

Analysis Procedures:

The experimental data was analyzed using statistical and computational methods to assess system performance. The fuzzy logic based control strategy was implemented in MATLAB/SIMULINK, where fuzzy inference rules were defined based on temperature and radiation variations. 3D fuzzy surface plots were generated to visualize the dynamic behavior of the system. Furthermore, a comparative analysis was conducted between different cooling scenarios (5 mm vs. 1 mm tedlar thickness and FLC implementation) to validate the effectiveness of the proposed approach.

NOMENCLATURE

Symbol	Description	Unit
A	Surface area of the hybrid collector	m^2
AFLC	Adaptive fuzzy logic controller	–
C	Specific heat capacity	$J \cdot kg^{-1} \cdot K^{-1}$
F	Packing factor	dimensionless
FLC	Fuzzy logic controller	–
G	Solar radiation	$W \cdot m^{-2}$
GO	Geometric optimization	–
h	Heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
M	Mass	kg
T	Temperature	K
t	Time	s
m	Mass flow rate	$kg \cdot s^{-1}$
V	Velocity	$m \cdot s^{-1}$
N_u	Nusselt number	dimensionless
P_r	Prandtl number	dimensionless
R_e	Reynolds number	dimensionless

GREEK SYMBOLS

α	Absorption coefficient	dimensionless
β	Solar cell temperature coefficient	K^{-1}
σ	Density	$kg \cdot m^{-3}$
τ	Transmittance	dimensionless
η	Efficiency	dimensionless
ϵ	Emissivity	dimensionless
e	Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
λ	Thickness	m

SUBSCRIPTS

a	Ambient
ab	Fin absorbers
c	Solar cell
cd	Conduction
cv	Convection
el	Electrical
f	Fluid
g	Glass cover
gr	Ground
i	Insulation
ra	Radiative
ted	Tedlar
th	Thermal

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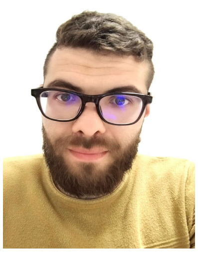

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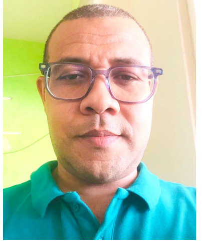

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