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Experimental and Modelling Assessment of Photovoltaic-Thermal Systems in Buildings at Desert Regional

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ABSTRACT
This study investigates the operational efficiency of a concentrated solar photovoltaic thermal flat-plate collector system equipped with heat-resistant triple-junction photovoltaic cells and two-dimensional tracking. The collector system employes linear receiver made of aluminum and copper cooling tubes. Both aluminum and copper tubes were assessed for their impact on the electrical and thermal efficiencies of the concentrated solar photovoltaic thermal system. The study results indicated that, despite aluminum tube heat absorbers being more cost-effective and readily available in local markets, they may not be the most suitable choice for achieving optimal performance in concentrated solar photovoltaic thermal systems. The electrical to thermal energy ratio for aluminum tube absorbers was approximately 18% to 50%, while it averaged 18% to 65% for copper tubes. Copper tubes demonstrated superior heat transfer performance compared to aluminum tubes, irrespective of the maximum temperature.
However, it is important to note that copper is vulnerable to solar radiation absorption, which can lead to elevated temperatures and subsequent alterations in heat transfer properties. These changes can have an impact on the overall thermal efficiency. In contrast to copper tubes, aluminum tubes experience a lower temperature increase when exposed to solar radiation within the concentrated solar photovoltaic thermal collector receiver. On the other hand, the electric output was slightly higher in the copper case when compared to aluminum tubes. Furthermore, the rate of water flow had a minimal impact on electrical efficiency, whereas thermal efficiency saw an improvement with an increase in flow rate.

***Keywords**: Receiver; Flat plate collector; Aluminum; Copper; Flow rate.*

1. Introduction

1.1. Statement of the problem

Recently, most developed societies have tended to exploit natural energy, especially solar energy, to generate electricity or use it directly to heat water and use it for different household purposes. Concentrated solar photovoltaic thermal collectors have thus gained increasing interest and subsequently the interest of the scientific community and industrial developers through their promising potential in advancing solar energy penetration within clean energy generation technologies. The concentrated solar photovoltaic thermal collector system concentrates solar heat in parallel and uses this heat to produce electricity and thermal energy, which can be exploited in various applications. The use of alternative energy sources is growing rapidly, and the use of photovoltaic solar energy has become increasingly important. It is the most suitable source for both electricity and thermal energy to decrease the global carbon emission [1]. The accumulation of different technologies of hybrid systems of photovoltaic in the building has been widely used nowadays. The growth is a direct result of a substantial increase in the number of homes, residential and service floor locations, leading to a rising demand for new technologies. The traditional photovoltaic panel does not reach even 25% efficiency because it converts a limited bandwidth of solar radiation to electricity. One of the recent studies focused on enhancing the performance of solar systems for heat and electricity production [2], It aimed to identify the most energy-efficient and effective design.. Solar energy is the most used renewable-energy source. The solar structures are primarily classified into two separate but similar categories, namely photovoltaic, and photovoltaic thermal systems, which transform solar energy into heat and electricity. Decreasing the performance of the photovoltaic modules with rising temperatures would make the problem more serious. The effective solution to this issue could be the use of coolant above or under photovoltaic modules to remove any excess heat from the modules. Moreover, the big challenge in photovoltaic thermal energy is given by the soiling and overheating of modules further reduces the energy conversion efficiency.

This research analyzed the effects of various glazing patterns on the system performance using a three-dimensional transient model. Also, the implications of several parameters on system operation, including tilt angle, azimuth angle, mass flow rate, and dust buildup on the system surface were included.

1.2. Background

There are some studies that explored the utilization of solar energy in pharmaceutical production factories, as demonstrated by Jaber et al [3] and the references cited therein. Some other parameters and modules have been investigated in [4], to show weather parameters effect such as temperature and solar irradiation on the photovoltaic (PV) performance and on the expected outcomes current and voltage. These investigations were simulated by MATLAB.

Solar modules typically convert over 60% of the incoming solar energy into heat [5]. Concentrated photovoltaic thermal systems generate both electrical and thermal energy by converting solar energy into heat energy through PV cells. Sandia National Labs fabricated the initial concentrated solar photovoltaic thermal panel in 2007 [6]. In the literature, numerous modeling and designs have been performed to enhance the performance of the PV and thermal power in the concentrated solar photovoltaic thermal system. Until now, multiple investigations have been carried out to assess the performance of these systems. Analytically and experimentally, the energetic performance of a ventilation naturally PVT system with the effect of the glass frame was examined in [7]. A novel system is capable of reducing power consumption by 56% compared to the traditional one[8]. Reference[9] conducted simulations to evaluate the performance of a PVT compound thermoelectric ventilator system under various operating conditions. In a separate study, Zhao et al.[10] optimized the design of a photovoltaic/thermal system that utilized both concentrated and non-concentrated solar radiation. Their findings indicated that an increase in solar irradiance had no impact on electrical efficiency, but significantly affected thermal efficiency. The authors achieved an overall efficiency of 66% for the concentrated solar photovoltaic thermal system. Moreover, Kandilli [11] discussed the theoretical model and the experimental results of a novel concentrating photovoltaic combined system based on spectral decomposition. In the last decade, the researchers focused on the two main parts of the system which are the photovoltaic system and the thermal part, including all the heat-transfer fundamentals, the module materials, the thermal conductivity of those materials, and the basics of thermodynamics. All these topics are essential to enhance the performance of the concentrated solar photovoltaic thermal systems (CPVT) as reported in Ref. [12]. Daghigh et al. [13] presented a review on the study of examining photovoltaic thermal (PVT) collector systems that used water and refrigerant as heat coolants. The authors demonstrated that the direct expansion solar-assisted heat pump is a more effective cooling method for PVT collectors. Furthermore, Royne et al. [14] showed a review of various methods that can be used for the cooling of the PV. The concentration ratio is one of the main factors to be considered in the concentrated photovoltaic thermal collectors. Experimental studies have indicated that the energy efficiency of PV modules in the systems is anticipated to reach 30% in Xu et al. [15]. While heat management is generally regarded as one of the most critical aspects to improve the uniform passive cooling of PV systems [16], [16], it was found that the heat drop reduced by 53% compared to other passive coolant systems.

In their study, Daneshazarian et al. [17] evaluated alternative options for concentrated solar photovoltaic thermal units and collectors. The primary collector types examined included linear parabolic trough, parabolic dish, and Fresnel lens reflectors. According to references [16, 17, 18], Fresnel lens reflectors were identified as the most suitable option for the systems, offering benefits in terms of size, weight, and cost. These systems can achieve a PV efficiency of 26%, producing 30 kW of electrical energy [19]. Overall, the efficiency of the systems has been reported to reach 75% [20].

One of the main advantages of the hybrid systems of the thermal and photovoltaic is overcoming the challenge of the high operating cost of the pure PV installations. The key disadvantage is the relatively high capital investment cost, as compared to the pure PV. Buonomano [21] created a simulation model to predict the performance of CPVT systems. An investigation of cooling cycles employing LiBr-H2O absorption fluids for both concentrated solar power and evacuated tubes was conducted using a simulation model for the performance of the cooling and heating dynamically of solar power systems. TRNSYS software was used to simulate the systems on MATLAB and confirmed that they agree with a prior model.

The advantages of PVT modules over PV modules opened its gate to the global market. It has a huge range of different applications such as residential applications, industrial, solar power stations and heat combined stations and some on-grid applications.

In the past, solar collection systems were employed for tourism purposes, as evidenced by a study conducted in Pakistan, which revealed that the main factors influencing the selection of solar heating systems were the cost and solar radiation, assessed using the TSol simulation tool [22].

In Saudi Arabia, the use of solar energy was implemented to achieve the goal of zero energy buildings. A study analyzed the energy consumption of two mosques in the Kingdom of Saudi Arabia (KSA) and identified areas where energy consumption could be optimized. This was considered a challenging application [23]. The thermal power produced could be used with different needs as food dryer, swimming pool heating, hot-water generation, space heating, industrial process heating, etc. PVT products are available in different countries of the Middle East.

One of the effective applications of photovoltaic thermal systems involves the integration of the PVT with a building integration photovoltaic thermal (BIPVT) system. The term BIPVT refers to a PVT device that is seamlessly incorporated into the building structure, combining the roof or exterior of the building, PV modules, and thermal collectors into a single package rather than individual installations. This approach has yielded notable successes in implementing PVT systems. This product combines conventional building materials and is more cost-effective than using multiple separate products. Its purpose extends beyond electricity production, as it also serves as noise insulation and provides sufficient thermal load for heating and cooling inside buildings [24]. The coolant PV airflow could be used in different applications and could be used as safeguard for the building against wind. With respect to the overall efficiency of electrical and thermal energy obtained from concentrated solar photovoltaic thermal system, Mortadi and El Fadar [25] showed that, the planned CPVT collector has the maximum primary energy efficiency. The results of the solar cooling systems' performance tests showed that a solar coefficient of performance (SCOP) of 0.488 is attained by the suggested concentrated solar photovoltaic thermal collector, which was followed by systems based on triangular, tubular, and rectangular receivers, each of them has a SCOP of 0.436, 0.406, and 0.367, respectively. Additionally, it has been demonstrated that the new CPVT design is the most economical one from an economic standpoint.

In the realm of industrial applications, PVT studies can be categorized into low-concentration PVT and solar collector of flat-plate PVT systems. Michael et al. [26] proposed an adaptive method to simulate the thermal photovoltaic module and examined the influence of various parameters such as climatological and architectural factors. Mraoui et al.[27] developed a mathematical model for a PVT hybrid solar collector using material tubes located under the cell to extract heat from the electrical PV module and enhance its electrical efficiency. A flat plate hybrid photovoltaic system has also been developed and designed in [28]. The researchers [29] and [30] developed an artificial neural network methodology to predict the system performance, while Yazdanifard et al. [31] studied the impact of flow rate on electrical and thermal efficiency. They also analyzed the effects of heat transfer with laminar and turbulent flow, as well as glazed and unglazed modules. The relation between concentration ratio and outlet fluid temperature was studied in [32], and it was found that the outlet temperature increases with the concentration ratio.

Nanofluids have higher thermal conductivity values than their base fluids, making them a promising option for use in thermal cooling systems. The incorporation of nanofluids in solar thermal systems can improve heat transfer coefficient, effectiveness, and overall thermal performance. Compared to mono-dispersed nanofluids, hybrid nanofluids offer even greater thermal conductivity. The use of hybrid nanofluids in solar thermal systems can improve fluid thermal properties, including thermal conductivity, density, viscosity, and specific heat. [33] provides a critical review of the synthesis, characterization, thermophysical properties, stability analysis, and application of both mono and hybrid nanofluids in solar thermal systems, specifically in flat plate collectors.

A CPV system in Egypt was simulated to estimate the electrical and thermal load for a small campus in Mansoura town, Egypt [34], and the effects of conduction, convection with/without wind, and radiation on the output thermal and electrical efficiency for a cylindrical tube were analyzed [35]. Modeling for parabolic trough with PV was also illustrated for domestic use in [36], where optimal working conditions and economic benefits were explained with cash flow and payback period. Peacock et al. [37] successfully investigated the potential of integrating novel spectral-beam-splitting (SBS), hybrid photovoltaic-thermal (PVT) collector, and organic Rankine cycle (ORC) technologies to maximize the use of solar energy for electricity generation while providing hot water and space heating to buildings. Generally, the efficiency of a CPVT system depends on several parameters, including the concentration ratio, temperature, solar irradiance, cooling method, tracking system, and PV cell efficiency. By optimizing these parameters, the overall efficiency of the concentrated solar photovoltaic thermal system can be improved.

1.3. Statement of the problem

The above introduction provides an overview of the increasing interest in the CPVT collectors as a promising technology to generate electricity and thermal energy from solar heat. It highlights the importance of renewable energy sources and the use of photovoltaic solar energy to decrease global carbon emissions. The text mentions recent studies that have investigated the performance of concentrated solar photovoltaic thermal systems under different conditions, including the effect of glazing patterns, weather, and concentration ratio. It also mentions some of the challenges in CPVT energy, such as the overheating and soiling of modules, and how they can be addressed by using coolants or by optimizing system design.

The current study investigates the performance of a linear trough focus concentrated photovoltaic thermal system prototype located at Heliopolis University for Sustainable Development, Egypt. The research experimentally examine the performance of the concentrated photovoltaic thermal system with cooler copper/aluminum water tubes. The concentrated photovoltaic thermal system has been fabricated using two distinct technologies, namely triple Junction PV, and flat plate receiver collector with copper and aluminum cooling tubes. The research objectives entail assessing the energy outcome of the system for each electrical and thermal component under various conditions. Additionally, the research tests a line through CPVT with Two-dimensional tracking and triple-junction PV cells and illustrates the electric, thermal, and overall efficiency. The research novelty lies in experimentally exploring the performance of the tubular receiver using flat plate techniques, which is significant because most receiver types in concentrated solar power systems use vacuum tube receivers that are not locally produced and involve high import costs. The results consider the impact of fluid flow rate, tube materials, and solar irradiation on the overall efficiency. Also, glassed, and un-glassed receivers have been used during the experiment to see the heat losses effect on the system's overall efficiency. The paper is organized as follows: Section 2 briefly describes the analysis of the methodology including materials and methods (CPVT experimental setup, the system overviews, and description of the prototype of CPVT modules). Section 3 introduces the thermal module (flat plat collector with Copper/Aluminum tubes and system heat gain and losses). Section 4 covers the main results and discussions of the research findings. The last section is devoted to the main conclusions drawn from the present research.

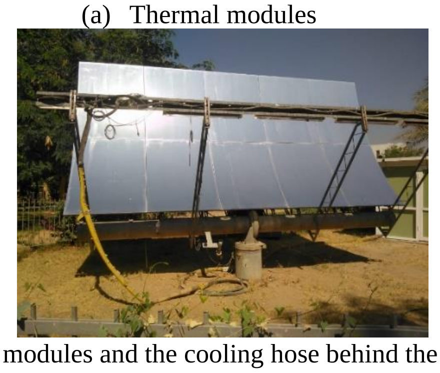
2. Materials and Methods

2.1. CPVT Experimental setup

Fig. 1 (a) illustrates the whole system of CPVT located in Heliopolis University, one of the five flat plat collectors' modules, which located at the CPVT receiver. One of the modules on receiver line is the triple junction PV, while the other four units are flat plate collector modules. **Fig.** 1 (b) shows that the five modules' units and the connection of the cooling pipes and the system are tracked to the sun.

The new prototype of the CPVT triple-junction GaInP/GaAs/Ge module was used with maximum temperature of 110^{o} C. Table (1) illustrates the technical data of the triple junction photovoltaic TJPV in a temperature range of 80^{o} C to 120^{o} C

(a) Thermal modules



(b) Five modules and the cooling hose behind the modules

Fig. 1 the tested modules

Table (1) Technical data of TJPV in a temperature range of 80º C to 120º C

Sun concentration MC/Glass	I_{sc} (A)	V_{oc} (V)	I_{MMP} (A)	V_{MMP} (V)	P_{MMP} (W)	FF (%)
X250	3.82	3.07	3.76	2.80	10.55	89%
X500	7.61	3.11	7.50	2.81	21.04	88.8%
X1000	15.36	3.15	14.98	2.70	40.46	83.8%

The light concentration process is typically characterized by the concentration ratio (C). By physical meaning, the concentration ratio is the factor by which the incident solar energy flux is optically enhanced on the receiving surface. So, confining the available energy coming through a chosen aperture to a smaller area on the receiver, should be able to increase. The concentration ratio (C) is defined as the ratio of the concentrated flux on the receiver to the ambient flux from the solar ratio. The concentration ratio (C) for this system is calculated by dividing the area of the receiver by the total area of the reflected mirrors (C = 144). Typically, a single-junction cell has a maximum efficiency of 33.16%[35] Multi-junction cells have shown a performance exceeding 46% [36]. The disparity between the normal application PV and the triple junction in which the first effect of the high temperature according to 0.45%/°C was commonly used in aerospace, while the second one is 21%/°C. The system consists of ten mirrors, which focus the sun beams. Along with the thermal unit, a 5.5 m long receiver is attached. The total area of the system is 17.5 m^2 having a geometrical concentration ratio of nearly 144. The year direct solar irradiation (DSI) has been measured by weather station located in El-Salam city (EGYPT) where the case study is located. The highest solar irradiance (w/m^2) was found in May, July, August, September, and April, respectively. The system of CPVT for both electrical and thermal units is described in Table (2). The system tracks around two-axes (Elevation and azimuthal motion). The system is designed to be 31.6 percent electrically efficient at 25 °C and 45 percent thermally efficient. The increase in the temperature of water in the closed tank is ranged from 30°C to 75°C with a flow rate of 66 l/hr.

Table (2) the system data specifications.

Data	Description	Unit	Value
1-General data	Concentration ratio	-	144
	Number of mirrors	-	10
	Total gross area of the mirror	m^2	19.315
	Tracking technology	Biaxial	-
	Azimuth range	Degree	0/270º
	Elevation range	Degree	-15/+90º
	Tracking control	Solar position algorithm + sun sensor feedback loop	
	Pointing accuracy	0.06	
	Operation ambient temperature	º C	20-80
	Thermal modules	Nr	5
2-Thermal data	Thermal peak power	kW_{th}	19.55
	Fluid	Coolant water	
	Maximum fluid temperature	º C	100
	Stagnation temperature	º C	160
	Max. operating pressure	kPa	200
3-Operating condition	Operating wind speed	km/h	40
	Permissible wind speed	km/h	130
	Weight of foundation	kg	1000
4-Physical dimensions	Height	m	4.2
	Depth	m	3
	Width	m	6.2
5-Efficiency %		85% DNI	

2.2. The system overviews

The concentrated solar power (CSP) system was designed to measure temperature, pressure, coolant flow rate and sun direction with different types of sensors for improving the system performance and monitoring the system status during the system tracking. It depends on different sensors to determine the position of the solar beams and other parameters:

- The pyrheliometer (LP PYRHE16): It directly measures solar irradiance in the unit of w/m^2. The surface which receives should be placed in a perpendicular manner relative with the rays of the sun.
- The sun sensor (ISS-AX): The ISS-DX sun sensor measures the incident angle of a sun ray in both orthogonal axes and the solar radiation. The high sensitivity reached is based on the geometrical dimensions of the design.
- The thermal modules have two thermocouples, one of them lies at the inlet and the other at outlet of the water.

These sensors are connected to programmable logic controller (PLC) and have two jobs:

Safety: if the temperature increases above the safe limit, the PLC will turn the system to sleep mode which was set to be 95°C.

Monitoring: displaying the sensor's output on the human machine interface (HMI).

2.3. Description of the prototype of CPVT modules

Fig. (2) shows the flowchart diagram of inputs and outputs of the electrical and thermal parts.

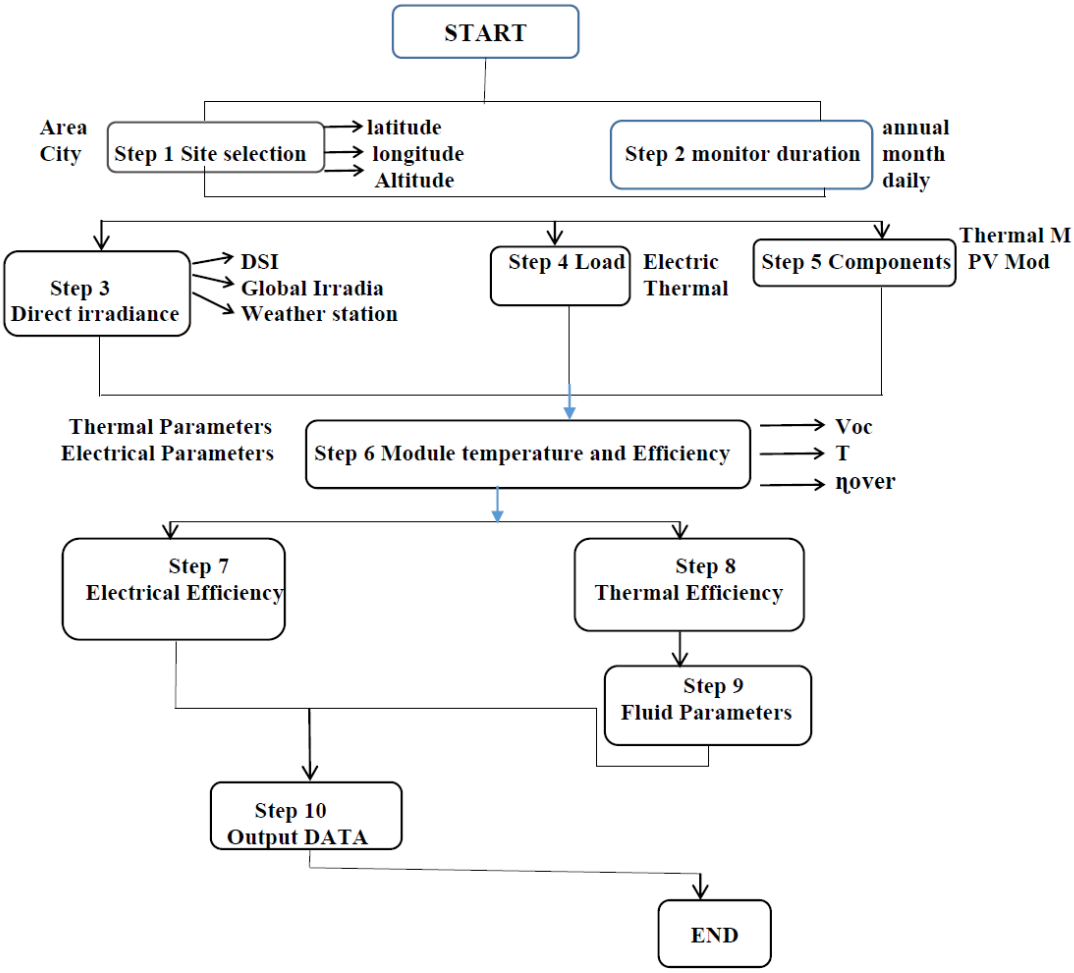


Fig. 2 Flowchart for CPVT model system, inputs, and outputs.

The overall performance of a CPVT system can be evaluated by the energetic (first law of thermodynamics) efficiency η_o, which is defined as the sum of thermal and electrical efficiencies [15]:

$$\eta_o = \eta_{th} + \eta_e \quad (1)$$

Where, η_{th} is the instantaneous thermal efficiency of the CPVT array, which reflects the heat conversion capability of the array. And η_e is the electrical efficiency for the photovoltaic, which represents the ability of the CPVT array to convert solar energy to electrical energy. Depending on the type of energy, the value of thermal and electric power varies. Given that electrical energy is converted from thermal energy to account for that value and save energy in CPVT. Considering the electrical energy as a high-grade form of energy gain, the energy saving efficiency (η_f) is also used. It is defined as:

$$\eta_f = \frac{\eta_e}{\eta_{power}} + \eta_{th} \quad (2)$$

where η_{power} is the electrical power generation efficiency for the conventional power plants.

Different shapes of modules have been investigated to generate the maximum thermal power [37]. The primary distinction between CPVT and CPV is that almost 50% of the portion of radiation energy, that is not converted into usable energy, is transferred to the heat extraction section as waste heat [38], [39]. Concerning the second law of thermodynamics, the ration of electrical power to thermal power is not equal. Extracted the relation between the electrical and thermal production as follow in [40], [41]:

$$E_{elec,eq} = \frac{E_{th}}{\delta} + E_{ele} \quad (3)$$

Studying the energy analysis of a CPVT collector which is in relation with second law of thermodynamics, is more important than the energy analysis based on first law of thermodynamics. Energy analysis is basic and considered as the best optimization method for CPVT collector.

Huang et al. [42] represented the Primary Energy Saving (PES) efficiency (η_{PES}) for a CPVT systems as follows:

$$\eta_{PES} = \frac{E_{th}}{\eta_{PES-th}} + \frac{E_{ele}}{\eta_{PES-ele}} \quad (4)$$

In the above equations, $E_{elec,eq}$ is known as the equivalent electrical energy cost, E_{ele} expresses the electrical energy, E_{th} is the thermal energy, δ is the electrical to thermal ratio, η_{PES-th} and $\eta_{PES-ele}$ are the efficiency of primary energy saving to thermal and electrical energy, respectively.

Since the performance of the PV has a greater influence on the system efficiency, the researchers have divided the power efficiency of the PV into three main efficiency equations, namely exergy efficiency, energy efficiency, and power conversion efficiency [42].

Linear relation form for the temperature dependent electrical efficiency of PV module (η_c) is developed in Ref. [43] :

$$\eta_c = \eta_{ref}[1 - ß(T_c - T_{ref}) + \gamma log G_T] \quad (5)$$

In which η_{ref} expresses the module's electrical efficiency at the reference temperature T_{ref} and at solar radiation of 1000 w/m^2. The coefficient of temperature ß and the solar radiation coefficient γ are mainly properties, ($ß = 0.004\ K^{-1},\ \gamma = 0.12$), for crystalline silicon modules.

The copper tubes could be a flat plate collector (FPC) of the hot climates, and evacuated tubes collectors (ETC) for cold countries. The latter, however, is usually taken as zero, as mentioned in Dubey et al. [44]and Eq. (5) is reduced to:

$$\eta_c = \eta_{ref}[1 - ß(T_c - T_{ref})].$$

Which represents the traditional linear expression for the PV electrical efficiency.

The system is considered as a starting point to reduce the cost of the product. When the cost of purchasing the product from the supplier reached 60,000 euros, the receiver was one of the most expensive items in the model. Therefore, the objective of the present research is to use a locally manufactured receiver to reduce the cost of the system by more than 30%. This research will be followed by a series of studies on the same system with the aim of reaching the lowest possible cost price for the product to be available for use, with spare parts and maintenance available continuously, without being dependent on currency rates or import movement.

3. The Thermal Module Analysis

3.1.1. Flat plat collector with (Copper/Aluminum tubes)

The flat plate collector, illustrated in **Fig. (3),** was covered by glass of thickness 2 mm to minimize the loss of convection heat, and reduce the transmittance of the long wave radiation. Hence, for the new flat plat collectors: thermal conductivity, emissivity, and thickness of insulation are the main parameters that should be kept in mind during the new manufacturing of cells. The area of mineral fiber insulation = 6 m², length of galvanized frame box, length L = 100 cm, width d = 15 cm, and height h = 10 cm. The area of the black metal sheet inside the frame was 120 × 80 cm² and a special glass of the thermal oven was used to build a module for the experiments. The advantages of this design are highly efficient for heat absorption and storage and having less emissivity through the thermal glass. The system has been also tested without glass and with the support of the type of thermal sealing. These types of heaters are characterized by rapid and easy installation (more stable) do not emit any noise and have the flexibility to use different tube materials.

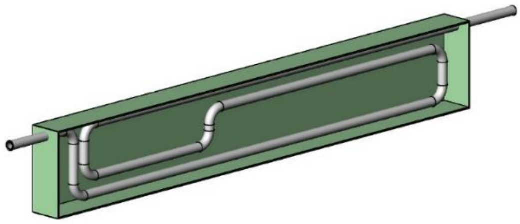


Fig. 3 Schematic Diagram of CPVT Collector.

The hydraulic cycle used to measure the solar thermal heat for the CPVT unit at Heliopolis University for Sustainable Development is shown in **Fig. (4).** Solar irradiation enters the photo voltage triple junction module where the heat rises and the water-cooling travels behind the module. Surface cooling starts based on the second law of the thermodynamics, which leads to heat transfer by convection from the cell to the atmosphere. The thermocouple gives the sign to the PLC to operate the solar pump to enable the water-cooling cycle in the system. According to the tested volume flow rate between 60 and 70 l/hr., the electric power could be adjusted to achieve the required temperature by setting the limit switch at the required temperature. The temperatures of inlet/outlet of the cooling water, ambient air, and photovoltaic were measured by

PT100 thermocouple. PLC was programmed to show the power measured from the system as electrical power and thermal power. One of the flexibilities of the system programming enabled the researchers to measure the current, and the DC voltage produced by the module. During the test, it was kept in mind for overheat protection when the outlet temperature reaches values more than 80°C, and the pressure of the hydraulic cycle increases to over 3 bars. It has then been controlled to switch off the system on sleeping mode to enable the temperature to dissipate by convection to the ambient air. A weather station has been installed on the system to measure the ambient temperature, solar irradiation, and wind speed in addition to the pyrometer. The pyrheliometer was mounted along with the system for measuring the direct normal irradiance (DNI). Table (3) illustrates the physical characteristics of the materials used [45]. The uncertainty analyses for the system were performed based on Holman's method and it can be defined as the root sum square of the instrumentation's fixed error and the detected random error during the measurements. Let's say a set of measurements is performed to assess "n" experimental variables. These measurements are used to find some desired results (R) of the experiment. Therefore, $R = R(X_1, X_2, \dots X_n)$. Let W_R is to be the uncertainty in the result and W_1, W_2, , ….., W_n are the uncertainties in the independent variables, the uncertainty can be calculated according to the following equation,

$$W_R = \left[\left(\frac{\partial R}{\partial X_1} W_1\right)^2 + \left(\frac{\partial R}{\partial X_2} W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n} W_n\right)^2\right]^{\frac{1}{2}} \quad (6)$$

The error or uncertainty in the result W_R is computed using Eq. (6) if the relationship between the measured parameters and the result is known as well as the measurement uncertainties of each quantity. The ratio between the output's least count and its least value is used to calculate the minimum error [45] . The percentage error of the solar power meter and the PT100 thermocouple were about 1.5 % and 0.3 %, respectively and these values are within the allowable range of the measurements.

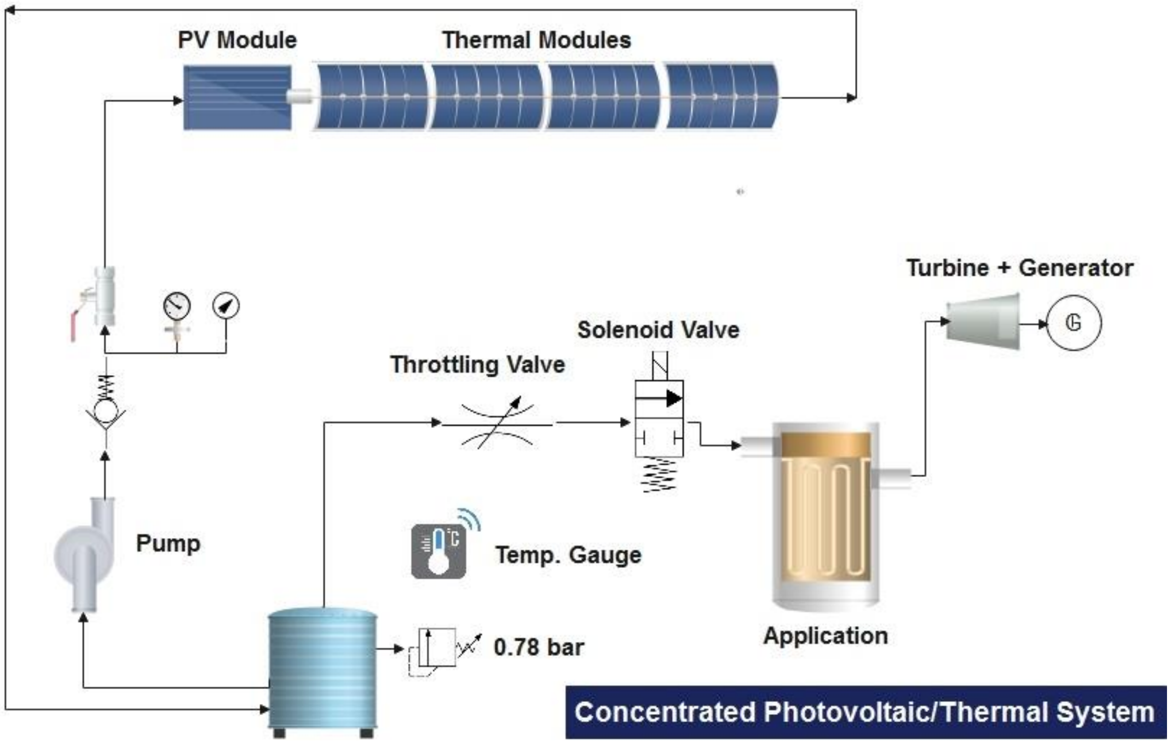


Fig. 4. Hydraulic diagram of the CPVT system.

Table (3) the physical characteristics of the materials used in the experiment

Parameter	Value
Receiver tube module	1.0 m
Absorber internal diameter	0.008 m
Emissivity of the glass frame	0.82
Absorber thermal conductivity for copper tubes	400 W/m.K
Thermal conductivity of water	0.6 W/m.K
Absorber thermal conductivity for aluminum tubes	205 W/m.K
Optical efficiency of glass envelops	0.8
Thermal conductivity of air	0.026 W/m.K
Air density	1.2 kg/m^3
Water density	1000 kg/m^3
Thermal conductivity of the glass	1.04 W/m.K
Dimensionless radiative heat transfer coefficient	0.96

3.2. System heat gain and losses

The temperature of the module is determined by the equilibrium between generated heat in the PV module by the sun and the conduction, convection and radiative heat loss from the module as shown in **Fig. (5).** The operating temperature of a PV module is an equilibrium between the heat generated by the PV module and the heat loss to the surrounding environment. There are three main mechanisms of heat loss: conduction, convection, and radiation [47] .

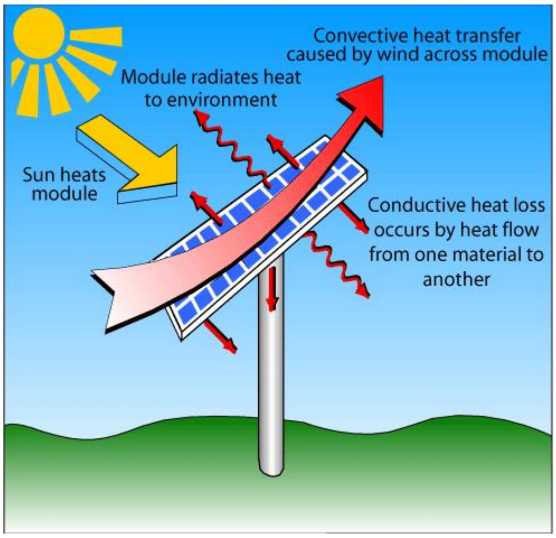


Fig. 5. Heat loss in PV modules

3.2.1. Conduction

For the coolant water in the experiment, the heat transfer along the coolant is a thermal energy and can be used in a certain application. The solar irradiance hits the triple junction and water moves behind the face of the PV to maintain the PV cell low as much as possible to keep the PV efficiency. To determine the outlet water temperature, the following equation displays the thermal power expected to produce in the outlet module:

$$Q_{th}^{o} = m^{o}c(T_{out} - T_{in}) = UA\Delta T_{ml} = UA\frac{(\text{Tout}-\text{Tin})}{\ln((\text{Tp}-\text{Tin})/(\text{Tp}-\text{Tout}))} \quad (7)$$

The heat transfer of the module is taking place from both the glass frame and the tubes of the flat plate collector. Equations 8 and 9 express the heat transfer in glass and tubes, respectively:

$$\text{Q(glass)} = K_{gl}\text{A}\frac{(\text{Tin - Tout})}{thickness} \quad (8)$$

$$\text{Q(tube)} = \frac{2\pi l K_{tube}(T_{in2}-T_{out2})}{\ln\frac{D_{out2}}{D_{in2}}} \quad (9)$$

3.2.2. Convection

The convection heat transfer depends on the properties of the coolant fluid including density and viscosity and if the fluid is forced or non-forced. In general, the heat transfer coefficient of the coolant water is 100-600 W/m^2·K for free convection (the convection heat transfer is natural) and 500-20000 W/m^2·K if there is forced convection.

The free convection occurs from the outer glass frame to the ambient using Newton's law of cooling:

$$q = h\pi D\,(T_{in} - T_{out}) \quad (10)$$

$$h = NuK/D \quad (11)$$

The relationship between the Nusselt number (Nu) value and the cross-section flow along the cylinder, where Reynolds and Nusselt numbers are obtained. The Nusselt number depends on whether the convection heat transfer is natural (no wind) or forced (with wind). To get the conventional heat coefficient, both free and forced cases have been used.

For the first conventional no-wind or free case, Nusselt number can be estimated from the following equation [48]:

$$Nu = \left\{0.06 + 0.387 \times Ra^{\left(\frac{1}{6}\right)} \Big/ \left[1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{10}}\right]^{\frac{9}{27}}\right\}^{2} \quad (12)$$

$$Pr = \frac{\gamma}{\alpha} \quad (13)$$

$$Ra = \frac{g\beta(Tout-Tin)D^3}{\alpha\gamma} \quad (14)$$

$$\beta = \frac{1}{Tsur} \quad (15)$$

This correlation is valid for $10^5 < Ra < 10^{12}$. *Ra* refers to Rayleigh number and *Pr* is Prandtl number for the outer glass cover, β is the thermal expansion volumetric coefficient, and α is the thermal diffusivity at temperature T_n and refers to the film temperature.

For case of forced convection, the Nusselt number could be obtained using Churchill and Berstein Equations with a range of ($Pr\ Re \geq 0.2$) as follow:

$$Nu = 0.3 + 0.62Re^{1/2}\ Pr^{1/3}\ \left[1 + \frac{0.4}{Pr^{2/3}}\right]^{-\frac{1}{4}} \left[1 + \left(\frac{Re}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \quad (16)$$

The assumption taks the isothermal condition with long horizontal cylinder. The movement of the fluid within the absorber tube will lead the correlation of Petukhov equation [49] to:

$$Nu = \frac{\left(\frac{f}{8}\right)Re\ Pe}{1+12{,}7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}}-1\right)} \left(\frac{d}{L}\right)^{2/3} \quad (17)$$

Taking the length of the tube and the outer absorber tube diameter into consideration, with neglecting any effect from the inner diameter:

$$f = (1.8\log Re - 1.5)^{-2} \quad (18)$$

3.2.3. Radiation

The radiation in the experiment occurs from the glassed cover of the collector to the surround and from the absorber tubes to the cover of the collector. The radiation from the outer glassed farm can be expressed by Stefan Boltzmann law at sky temperature T_{sky}.

$$Q_{Rad} = \sigma\varepsilon\pi D_g\left((T_g^4 - T_{sky}^4\right) \quad (19)$$

The radiation from the absorber tube will be neglected for the assumption that all long wavelength radiation is absorbed within the fluid internal layer.

Due to the thermal losses from the module to surround, there will be heat losses by conduction from the back and side of the collector. There are also heat losses by convection from the glass frame. Radiation will also occur from the glass sheet depending on the type of the glass sheet and the wavelength reflected from the glass. The typical equation describing the conduction heat transfer for a plane surface is:

$$Q = hA\,\Delta T \quad (20)$$

where h is the heat transfer rate (W/m^{2}K); A is the area of the collector (m^2); ΔT is the temperature difference between the surface of the collectors and the ambient.

1. Concentration ratio: The concentration ratio is the ratio of the area of the reflector to the area of the PV cell. A higher concentration ratio means that more sunlight is concentrated onto the PV cell, increasing the electrical output. A typical concentration ratio for a CPVT system is between 50 and 500.
2. Temperature: The temperature of the PV cells and thermal collectors affects their efficiency. PV cells become less efficient as their temperature increases, while thermal collectors become more efficient at higher temperatures. The optimal temperature for a CPVT system is typically between 50°C and 90°C.
3. Solar Irradiance: The amount of solar radiation or irradiance that reaches the CPVT system affects its electrical and thermal output. Higher solar irradiance leads to higher electrical output, while thermal output is affected by the temperature difference between the collectors and the environment.
4. Cooling method: Cooling methods are used to maintain the temperature of the PV cells within their optimal range. With water cooling being more efficient while, it could be more expensive.
5. Tracking system: The tracking system used to follow the sun's movement affects the efficiency of the CPVT system. Single-axis and dual-axis tracking systems are common, with dual-axis systems being more efficient but also more expensive.
6. PV cell efficiency: The efficiency of the PV cells themselves is a critical parameter that affects the overall efficiency of the CPVT system. Higher efficiency PV cells produce more electricity for the same amount of sunlight.

4. Results and Discussions

During the team investigations and experiments, the concentrated photovoltaic system's efficiency is affected by several parameters, including:

In this study, the model has been run daily for a year and results were registered in the system evaluation for electrical, thermal and energy efficiency of CPVT. The main characteristics have been realized with the tube materials, the flow rate, the tube diameter, and solar irradiation effect on the system CPVT efficiency. The flat plate collector principles allowed for examining the three ways of heat transfer: conduction, convection, and radiation. The laminar and turbulent flows were tested in relation with the flow rate and both electrical and thermal efficiencies have been estimated. The radiation heat transfer was tested by glazed and unglazed system of the flat plate collector. The efficiency of glazed and unglazed photovoltaic thermal collectors can vary as a function of solar radiation. As the intensity of solar radiation increases, the efficiency of the PVT collector typically increases up to a certain point. Beyond this point, the efficiency may start to decline due to overheating. The cover of a photovoltaic thermal unit can have a significant effect on the efficiency of the unit. In a glazed PVT unit, the cover serves as a protective layer for the photovoltaic cells and can help to increase the efficiency of the unit by reducing the amount of heat loss. The type of glazing material used can also affect the transmittance of solar radiation, which can impact the amount of solar energy that is able to reach the photovoltaic cells. Unglazed units do not have a protective cover, so they are more vulnerable to the effects of extreme weather events such as hail and high winds. However, unglazed units can be more durable and long-lasting than glazed units in certain environments equation.

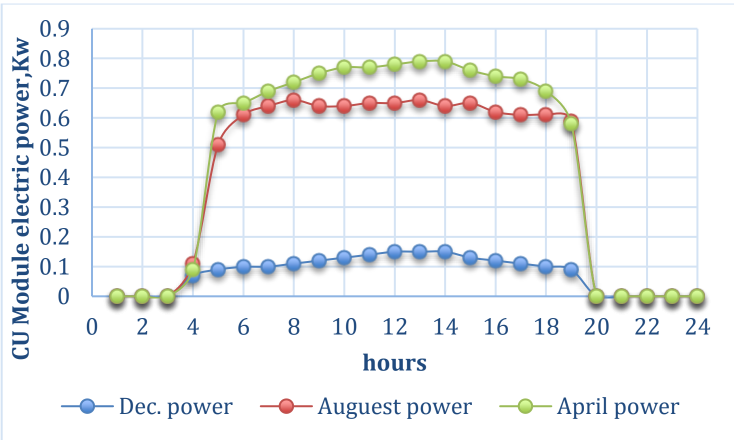
It is clear, that several important applications of solar energy can change the lifestyle in world by reducing the usage of the fossil oil and reducing the carbon emissions equation.

The technical data of the triple junction cell has been shown and the technical data of the CPVT system and the concentration ratio have been also introduced. There were 24 cells per triple junction model. The results of the solar irradiation were obtained from the weather station located in Heliopolis University. Its geographical location is latitude and longitude (N30.15304652, and E31.432176, respectively) at an elevation 67m.

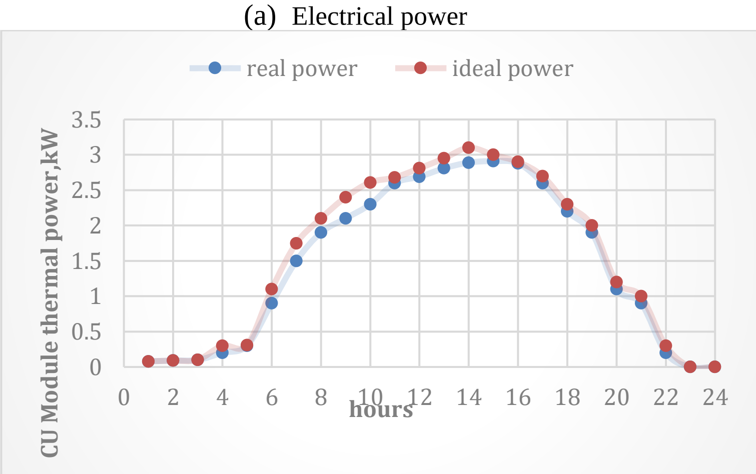
4.1. Effect of tube materials

Fig.s (**6**) and **(7)** depict the electrical and thermal powers of a concentrated photovoltaic-thermal system over a three-month period (April, August, and December) for copper and aluminum tubes. Notably, the average electrical power generated by both copper and aluminum tubes was found to be steady during the day time. However, the electric output slightly higher in the copper case than the aluminum tubes, as demonstrated in **Fig.s** (6)(a) and (7) (a). However, during noon hours, the solar irradiation intensifies, resulting in elevated module temperatures and consequently higher thermal power output in Cu tubes. During summer months, when incident solar radiation increases, the temperature of the solar cells also rises, leading to greater heat dissipation from the triple junction cell through the cooling water.

It can be observed in **Figs.** (6) (b) and (7) (b) that there is a good approximation between the theoretical (ideal) and the actual measured (real) evolution heat gain of receiver, which is variant around the day from sunrise to sunset periods to reach the maximum value 3000 watt (Cu-tubes of flat plate module) and 2600 watt (Al-tubes of flat plate module) around 02:00 PM in the afternoon in June, then it starts to drop during the day. The two-material tubes are close to the scale of conductivity, but Cu-tubes module has more desirable characteristic. The conductivity of copper tubes is about 337-386 W/m.K at 20°C while that of aluminum tubes is about 205-235 W/m.K



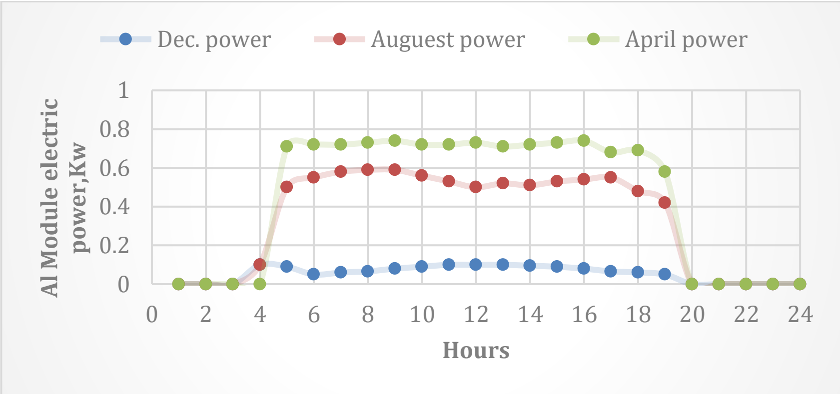
(a) Electrical power



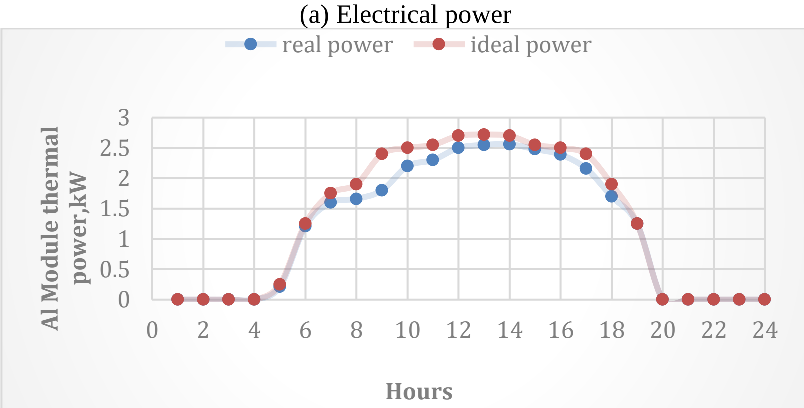
(b) Thermal power

Fig. 6. Electrical power and thermal power of the CPVT with Cu-tubes of flat plate module

Regarding the heat transfer process, the copper-tubes absorber is better than the aluminum-tubes absorber that is why the most tubes of coolers are made of copper. Aluminum is however lighter, and it is used for mostly all radiators and fins on water-cooling rids where weight is a concern. Some of the best computer coolers and water-cooling radiators are made up of both copper and aluminum. However, if the collector is not covered by glass, however, Cu tubes will get tarnished, Al tubes won't have this problem.



(a) Electrical power



(b) Thermal power

Fig. 7 Electrical power and thermal power of the CPVT with Al-tubes of flat plate module

4.2. Effect of the solar irradiance

The collector tubes play a critical role in the output power expectancy. The most popular forms of the tubes were noted as copper (Cu) tubes for the flat plate collector techniques. In experimental investigations, copper has exhibited superior heat conductivity due to its high thermal conductivity, leading to rapid and efficient heat transfer. Nevertheless, copper is susceptible to solar radiation absorption, which can lead to increased temperature and consequential heat transfer property alterations that impact the thermal efficiency of CPVT systems. Conversely, aluminum has lower thermal conductivity compared to copper, but its subpar solar radiation absorption properties make it a suitable alternative for CPVT receiver tubes that will be exposed to direct sunlight. As a result, aluminum tubes will encounter less temperature elevation when subjected to solar radiation in the CPVT receiver compared to copper tubes. **Fig. (8)** shows the total efficiency (η_o) for both Cu and Al against the solar irradiance.

When the solar radiation (G) rang is from 300 to 320 w/m^2 and the flow rate is 60-70 l/hr, the range of thermal efficiency for the copper tubes has varied from 37-57% while the range of the thermal efficiency with aluminum tubes has varied from 21-50%, see Figs. 8 and 9. The electrical efficiency has reported values from 16-21% for the type of triple-junction PV. The theoretical value of triple-junction PV is recorded with the manufacturing up to 40%.

A combination of heat tube based CPVT can significantly improve the total efficiency. The thermal energy of the system typically increases with solar irradiation, but the electrical efficiency and overall efficiency decrease. Also, for the ambient temperature increase, the thermal power increases, and the electrical power drops. The increase in the packing factor of the photovoltaic results in a decrease in thermal power and an increase in electrical power.

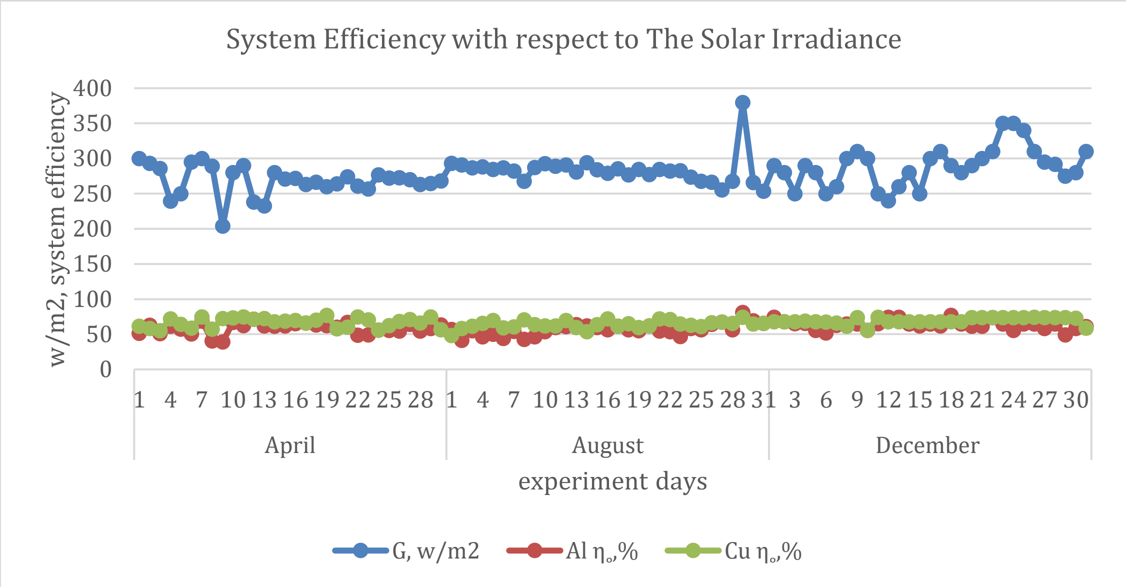


Fig. 8 Variation of Cu & Al system efficiency with solar irradiation (w/m^2) at different months.

Thermal conductivity for the two types of modules has been selected for both copper and aluminum tubes. The quantity of heat transmitted through a unit thickness of a material in a direction normal to a surface of the unit area is due to the unit temperature gradient under steady-state conditions. For the performance of the thermal modules, **Fig**s. (9) and (10) illustrate the thermal and the electrical efficiencies for both copper and aluminum tubes, respectively versus a day record date of June month. It is shown that the electrical efficiency is almost constant during the daytime while the thermal efficiency is varied during the daytime according to the solar irradiance and temperature difference between the inlet and outlet.

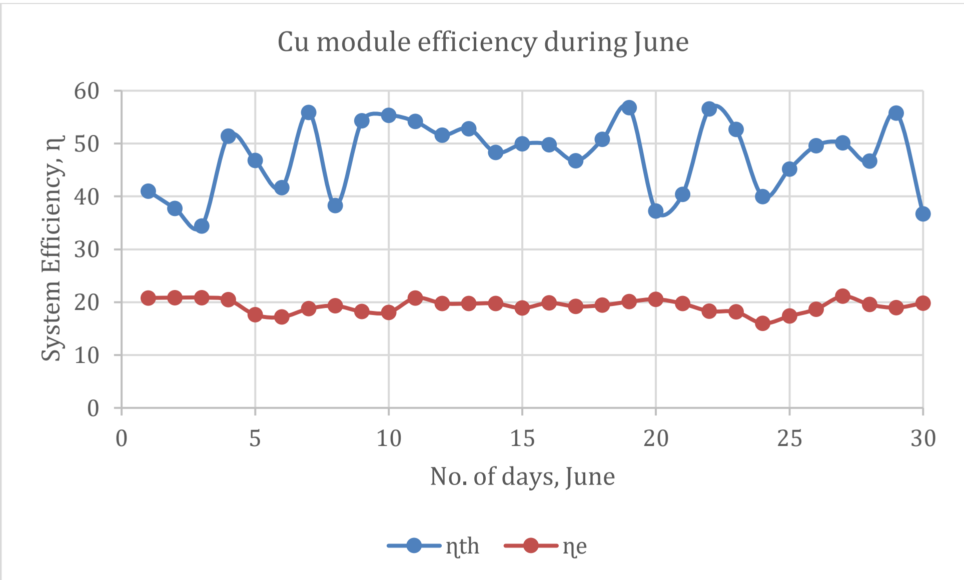


Fig. 9. The electrical/thermal efficiency verses the day record date of June month for Cu module.

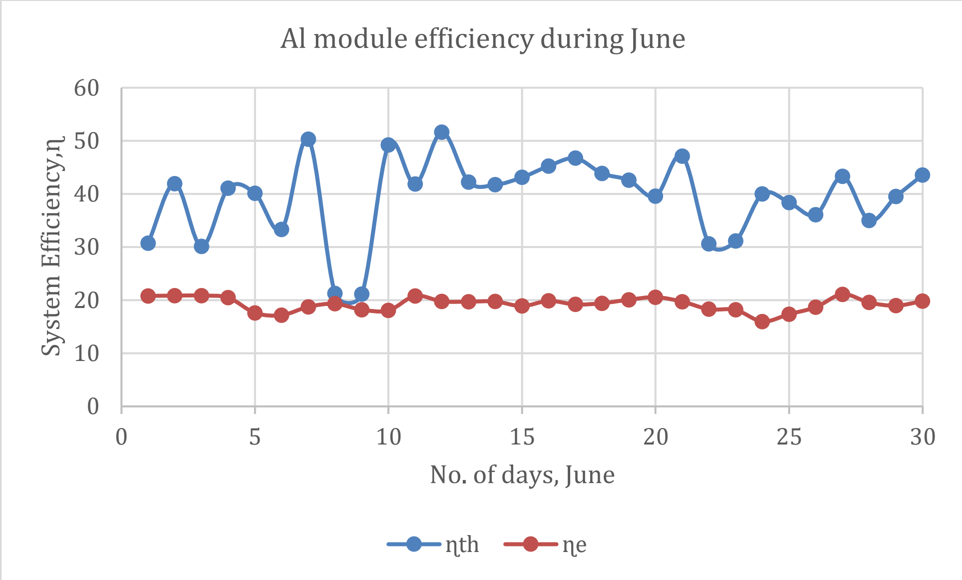


Fig. 10. The electrical/thermal efficiency verses the day record date of June month for Al module.

Fig. (11) illustrates the temperature of the inlet and outlet for both Al/Cu tubes modules recorded during June month. However, the temperature goes higher for Cu due to the higher thermal conductivity of the copper.

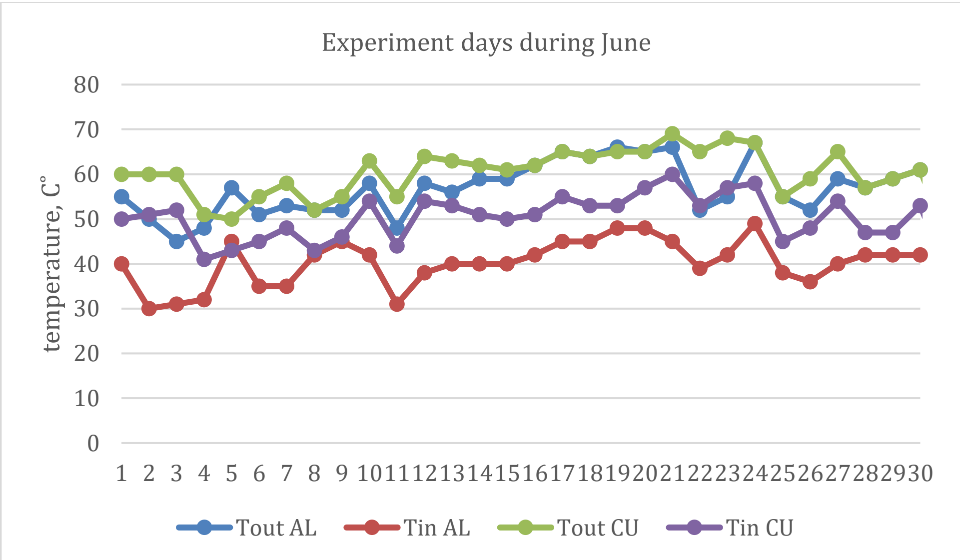


Fig. 11 The temperature vs. daytime in June for Al/Cu tube modules.

4.3. Effect of the flow rate

For the effect of the flow rate ranged from 0.001and 0.0194 liter/sec on the temperature of PV and the outlet temperature is shown in **Fig.** (12). The electrical, thermal, and overall efficiencies of CPVT have been calculated using working fluid of water for the coolant process and shown in **Fig.** (13). The direct solar irradiance was estimated 300-400 w/m^2. The coolant fluid absorbs both infrared and visible light. When both thermal and PV units are separated, both have a little effect on each other. For the triple junction PV, the maximum temperature according to the data sheet (Table 2) is 120^{o}C, therefore, as shown in **Fig.** 12 and confirmed by **Fig.** 13, the impact of flow rate on the temperature of the photovoltaic (PV) module and its electrical efficiency has been investigated. It was found that the flow rate has a negligible effect on the temperature of the PV module, which remains stable at around 34°C. Similarly, the electrical efficiency of the PV module remains constant and independent of the flow rate. **Fig.** 12 illustrates that the CPVT system's outlet temperature decreases with increasing flow rate, ranging from 0.004 to 0.0194 l/s. This reduction in temperature is due to the conversion of thermal power, with no impact on the electrical efficiency (as seen in **Fig.** (13). It can therefore be concluded that the electrical efficiency is not significantly affected by the water flow rate, while the thermal efficiency increases with increasing flow rate.

During the measurements, the use of a circulation pump to increase the Reynolds number (flow rate) resulted in improved heat transfer, which agreed with Yazdanifard et al. [49], therefore, a system with a pump operating in the laminar flow range may have lower thermal and electrical efficiencies due to the reduced flow rate.

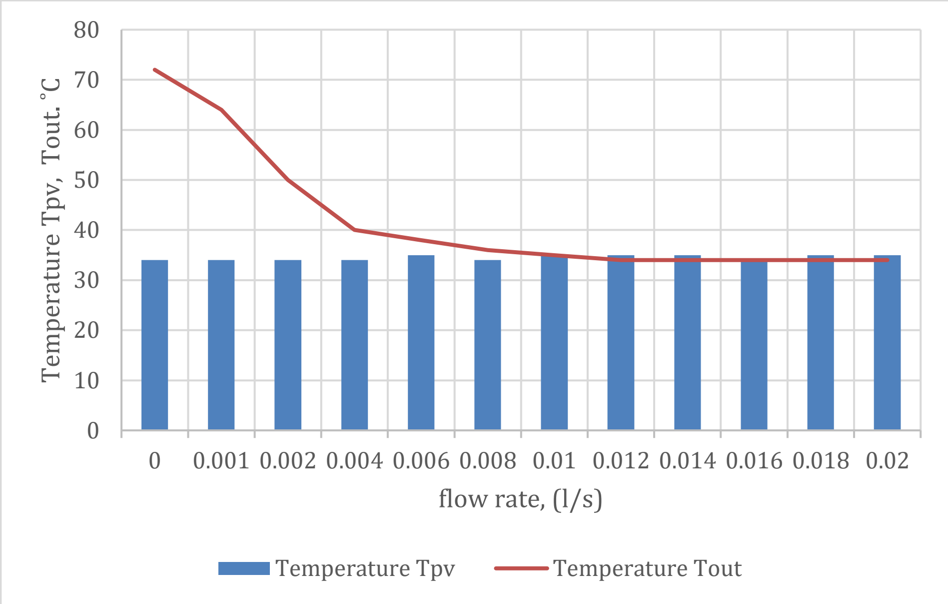


Fig. 12 The relation between T_{PV} and T_{out} with the coolant flow rate.

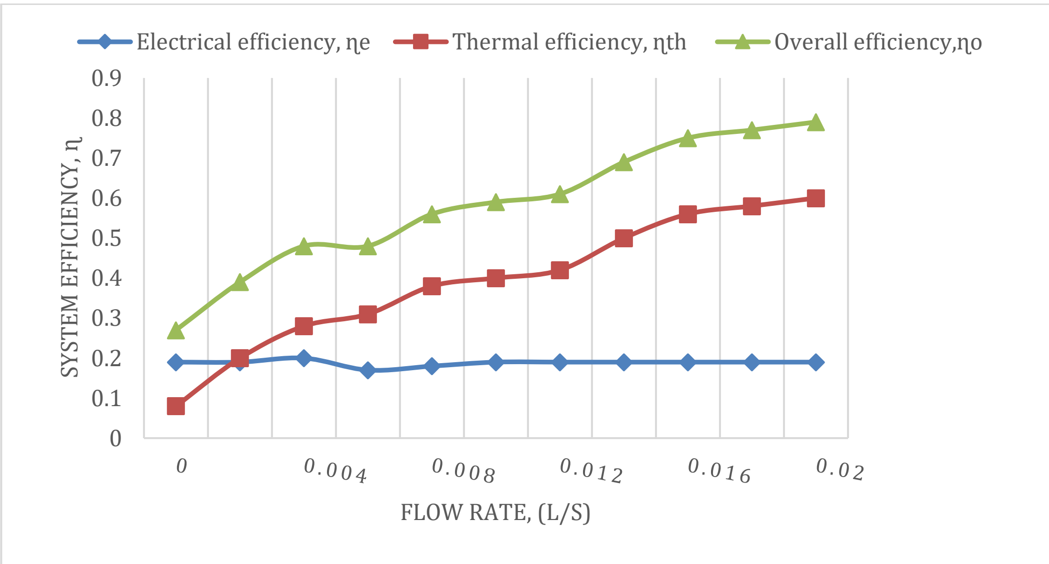


Fig. 13 The electrical, thermal, and overall efficiency of CPVT verse the flow rate

5. Conclusions

In this research, the effects of various parameters on a water-cooled CPVT system were experimentally and analytically investigated in different cooling flow rate through the cooling tubes. The present CPVT system records the performance of two different flat-plate collectors using Cu/Al cooling tubes realizing that the Al-tube system is better due to manufacturing cost and flexibility. The main results of the present study led to the following remarks:

- Generally, the glazed CPVT system generates higher total energy efficiency compared with unglazed one.
- The efficiency of PV is varying from 15-26%, as the percentage is going up when the ambient temperature and the solar irradiation are at low values and drop when the ambient temperature and solar irradiation increase. The reverse happens with the thermal efficiency varying from 37-57% for the copper-tube collector and 21-50% for the Al-tube collector.

- Although, in the Cu-tube module, heat transfer is improved, copper is more expensive than Al-tube one.
- For the whole system of the CPVT, heat transfer fluid runs through the tube to absorb the concentrated sunlight. It increases the temperature of the fluid, which can then be used to heat for an application like a steam turbine in an electric generator. The method is economical and has a thermal efficiency between 60-75% for the tube.
- Maximum (ideal) collector efficiency is determined to be 75%, and the electrical to thermal power is 32-44%.
- The overall efficiency of the system could be set as 30% electricity to 70% thermal.
- The two materials of the tubes used for the experiments give a clear vision that copper tubes for cooling solar collectors will give better results for the heat transfer, but if the maximum temperature is not the main concern, hence the cost-effective of aluminum tubes will play a great role against the use of copper tubes.
- The electrical efficiency of the glazed-frame CPVT system versus hours is almost constant during the daytime where the thermal module varies according to the solar irradiating, and cooling flow rate.
- The glazed frame CPVT, which has an increased efficiency with reducing the amount of heat loss, is not significantly affected by the water flow rate in either copper or aluminum cooling tubes.

  While CPVT technology systems have the potential to provide high efficiency and reduce the cost of solar energy production, there are uncertainties and costs associated with the technology. The cost of CPVT systems is currently higher than traditional photovoltaic systems, and the technology is still in the early stages of adoption. Additionally, there are technical, economic, and market uncertainties that need to be addressed to fully realize the potential of CPVT systems.

The solar concentrator system utilized in Heliopolis University was the first step towards manufacturing a significant and impactful component of the device. Furthermore, replacing the evacuated tube system with a flat plate collector system had a positive impact on the cooling process of the electrical part. This change has opened doors for future research, which may include topics such as cost, efficiency, fluid selection, receiver type, and system geometry.

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Nomenclature

A	Area (m^2)
A	Constant
AM	Air mass
C	Concentration ratio
C	Specific heat (kJ/kg K)
CPV	Concentrating photovoltaic system
CPV/T	Concentrating photovoltaic thermal system
DNI	Direct normal irradiance (kWh/m^2)
F	Safety factor
G_0	Solar constant (w/m^2)
G_{dir}	Direct solar irradiance (kWh/m^2)
$G_{dir,r}$	Real direct solar irradiance (kWh/m^2)
H	Altitude (km)
HRA	Hourly angle (◦)
InGaP/InGaAs/Ge	Indium–gallium–phosphide/indium– gallium–arsenide/germanium
K	Conductive conductance (W/K)
k_t	Thermal coefficient
LST	Local solar time (h)
LSTM	Local standard time meridian (◦)
LT	Local time (h)
$\dot{m}$	Mass flow rate (kg/s)
n	Days number
n_c	Cells number
P	Electric energy (kWh)
Q	Thermal energy (kWh)
$\dot{Q}$	Thermal power (kW)
T	Temperature (◦C)
TC	Correction factor (min)
U	Unitary global conductance (W/m^2 K)
V_{0c}	Open circuit voltage (V)
ΔT	Temperature difference (◦C)

Greek symbols

H	Efficiency
Δ	Electrical to thermal ratio
E	Emissivity coefficient
ω_s	Hour angle of astronomical sunset (◦)
φ	Latitude (◦)
ρ	Reflectivity coefficient
σ	Sfefan–Boltzmann constant ($W/(m^2 \times K^4)$)
α	Solar elevation (◦)
σ_t	Temperature coefficient (%/◦C)
η_{th}	Thermal efficiency
η_o	Total efficiency
τ	Transmittance coefficient
θ_z	Zenith angle (◦)

Subscripts

c	Cell
I	Current (A)
η_e	Electrical efficiency
f	Fuid
h,e	Heat exchanger
id	Ideal
in	Inlet
inv	Inverter
l	Loss
L	Liters
m,w	Mains water
mod	Module
opt	Optic
out	Outlet
PES-ele energy	PES-ele primary energy saving to electrical energy
PES-th energy	PES-th primary energy saving to thermal energy
PV	Photovoltaic
P	Plate
PES	Primary energy saving
H	Heat transfer coefficient, $W/m^2.K$
th	Thermal
W	Water