RESEARCH PAPER

Experimental and Theoretical Investigation of Solar Energy Utilization for Water Cooling Systems: Prospects of Nanotechnology for Enhanced Photovoltaic Performance

Eman Shaker Hussein* *, *Shaymaa Hamza Anbr Swadi

Department of Mechanical Engineering, Faculty of Engineering, University of Al Qadisiyah, Al Qadisiyah, Iraq

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ABSTRACT

The increasing demand for sustainable and renewable energy technologies has encouraged the adoption of solar-powered cooling systems. However, one of the major challenges in such systems is achieving reliable and continuous operation through proper sizing and voltage matching of photovoltaic (PV) components. The problem addressed in this study is the inability of improperly designed solar-powered water cooling systems to maintain stable performance for extended operating periods due to power and voltage limitations. The main objective of this research is to investigate experimentally and theoretically the feasibility of utilizing solar energy to power a water cooling system and to determine the optimal system configuration required for reliable operation. Specifically, the study aims to evaluate system performance, identify design limitations, and develop an improved configuration capable of meeting the desired operational requirements. To achieve these objectives, the study was divided into two main parts. The first part focused on theoretical calculations and system design. Based on the design calculations, the initial configuration consisted of six 100-W photovoltaic panels, four 1000-W 12-V inverters, charge controllers, and four batteries. However, practical testing revealed a significant voltage drop after approximately three hours of operation, causing system failure. Therefore, in the second part of the study, the system was redesigned and experimentally evaluated using an improved configuration consisting of eight photovoltaic panels and four 1000-W 24-V inverters while maintaining the same number of batteries and charge controllers. The system was installed and tested on the Renewable Energy Laboratory rooftop. Performance indicators including output power, current capacity, photovoltaic panel surface temperature, conversion efficiency, and operating duration were measured and analyzed. The experimental results demonstrated that the modified configuration successfully operated the water cooling system continuously for eight hours and achieved the required performance specifications.Future improvements may include the application of nanotechnology-based coatings or nanomaterials to photovoltaic panels to enhance light absorption, reduce surface temperature, and potentially improve conversion efficiency. The findings confirm that appropriate system sizing and voltage configuration are critical factors in ensuring the stability and reliability of solar-powered water cooling systems. This study provides practical guidance for the design and implementation of similar solar cooling applications under comparable environmental and operating conditions.

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* *Corresponding Author Email: eman.hussein@qu.edu.iq*

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INTRODUCTION

The photovoltaic PV systems' electrical efficiency typically falls between 6% and 17%. Thus, a significant portion of the energy from the sun that strikes a PV system is converted into thermal energy, which raises the temperature of the solar cells and, subsequently, reduces their efficiency [1,2] indicate that an increase in the temperature of the solar cells (1 Kelvin or 1°C) will decrease the photoelectric conversion efficiency by approximately 0.2% to 0.5%. The continued high operating temperature of the PV systems will increase degradation of the solar cells, leading to a shorter useful lifetime of the solar cells. The findings demonstrate the need for effective ways of cooling the PV systems. In this context, nanotechnology-based materials and nanostructured coatings have attracted increasing attention as promising approaches for improving photovoltaic performance by enhancing light absorption, reducing surface temperature, and improving the thermal management of PV cells. The most common way to cool PV systems is with liquid (water) based cooling technologies [3]; however, heat pipe technology is now becoming available as an effective alternative means to cooling PV systems [4].

significant increase in the amount of research and development from science and engineering in trying to lessen the environmental effects caused by our current methods of using energy [5]. Global warming is a result of the large amounts of carbon dioxide (CO_2) being released into the atmosphere because of the burning of fossil fuels for energy (e.g., coal, oil, natural gas) plus other gases like methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). In addition to global warming, rapid population growth and economic growth of emerging economies have led to overall increases in energy consumption globally; it is expected that between 2003 and 2030, total worldwide energy consumption will be up approximately 71%, and fossil fuels will continue to contribute the largest single share of energy fuel for this time period and will therefore remain the largest contributor to human-caused climate change. They are available in so many places around the world and have less impact on the earth's environment than current energy sources [6]. Solar thermal technology can be used in many ways and would create numerous opportunities to produce domestic hot water (DHW) for residential customers and for space heating (and even cooling) of homes or businesses. Solar DHW systems are already being used by many people as they provide enough thermal energy to heat homes with only sunlight. On the other hand, air-conditioning systems account for a large portion of the energy consumed by buildings, and they also produce high-demand electric loads during the summer months. As such, solar-assisted cooling systems can be seen as one of the ways to both reduce energy consumption from traditional air-conditioning systems and reduce environmental footprints [7]. Solar energy use varies significantly by region, depending on local laws, availability of technologies, and economic incentives. Solar energy, primarily used for heating water, is very well developed and established in China and many regions throughout Australasia. Extensive use of solar energy for residential and commercial applications has been promoted by government subsidies throughout Europe. Comprehensive use of solar energy technologies exists for large-scale desalination and absorption-style cooling in the Middle Eastern region. On the other hand, solar technology usage in the U.S. remains very limited and to some extent relies upon tax incentives and utility-financed programs that largely react to energy price changes or to limited availability of energy supplies [8]. Technologically capable countries (e.g., the United States) have implemented substantial amounts of installed technology to create integrated Renewable Energy systems nationwide. Renewable Energy projects involving solar energy began in Romania in the late 1970's (1979), with residential systems for domestic hot water supply (DHW) being installed throughout the country (initially). Timișoara was the very first place to have an entire district outfitted with these systems, and the area was named "Zona Soarelui" (Sun Zone). More recently, technology has been added as a component of agricultural and industrial use [9]. The amount of direct solar radiation that reaches the surface is very much dependent upon the orientation and tilt of that surface; however, the amount of diffuse solar radiation that reaches the surface is isotropic. Fig. 1 illustrates how the total amount of diffused sunlight contributes to the total amount of solar irradiance received on a given surface on the Earth's surface [10].

Recent studies have focused on improving the efficiency and reliability of solar-powered water cooling systems through advanced

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photovoltaic technologies and optimized thermal management techniques. Researchers have investigated various cooling methods to enhance energy conversion efficiency and maintain stable operating temperatures. Experimental results have demonstrated the feasibility of utilizing solar energy as a sustainable power source for water cooling applications. These developments highlight the growing importance of renewable-energy-based cooling systems in achieving energy conservation and environmental sustainability.

If the weather is perfect - there is no haze or fog blocking the rays, minimal air pollution and the rays of the sun are coming down at a 90 degree angle - then you will collect about 1000 W/m² per square metre of land on the surface of the planet during the middle of the day. At this time and place, this will occur in most of Europe: Western, Central and Eastern. Peak values of the total amount of solar radiation received at the Earth's surface will be composed of the direct sunlight and the diffuse sunlight. The way in which solar energy is modulated by the Earth's atmosphere is primarily due to two physical phenomena: absorption and scattering. When solar energy is absorbed, it turns into heat energy; but scattering redistributes energy around the Earth isotropically (equally in all directions) providing the diffuse component of surface irradiance. Atmospheric clouds and cloud types, as well as other meteorological factors, affect the amount of energy received on the ground. Romania has high potential for solar energy production due to its latitude, its climate being temperate and its geographical location within Europe. A flat surface of 1 m² skyward, perpendicularly oriented to incident rays, can produce approximately 900 to 1450 kilowatt hours (kWh) per year based upon variables such as Average Daily Solar Irradiance (ADIR) and regional elevation, latitude, and seasonal variations. The ADIR for the summer months can be 5 times higher than during the winter months; however, on an optimal winter day (e.g., clear sky and low humidity), the daily irradiation values are still between 4 and 5 kWh/(m²/day), therefore solar energy is relatively independent of the ambient temperature. In order to illustrate this potential, it is estimated that Romania receives approximately 285,000,000,000 MWh/year of solar energy, while Romania's total annual energy consumption in 2011 was approximately 260,900,000 MWh. Thus, theoretically, this solar energy resource could meet Romania's energy demand for over 1,090 years, demonstrating the significant amount of untapped solar energy available in Romania's national energy generation portfolio [11].

Solar-powered cooling systems are typically classified into three main categories:

Solar Electrical Cooling – where solar photovoltaic (PV) panels generate electricity to drive conventional refrigeration systems.

Solar Thermal Cooling – utilizing solar thermal collectors to power absorption or adsorption refrigeration cycles.

Solar Combined Power and Cooling – integrated systems that simultaneously produce electricity

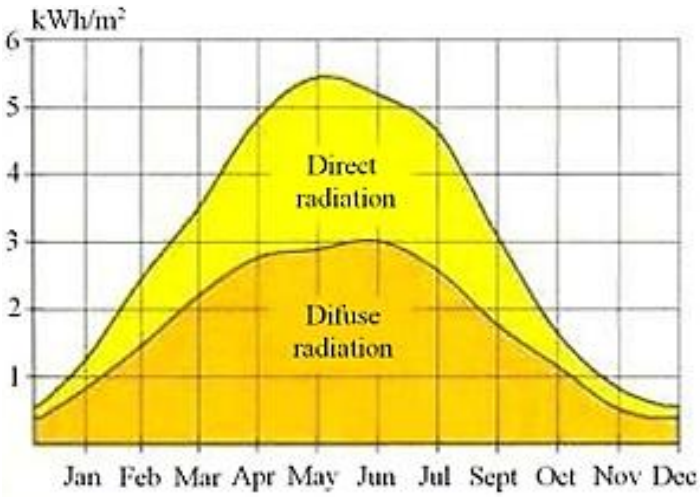

Fig. 1. Total and diffuse solar radiation [10].

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and thermal energy for cooling.

Solar thermal energy can be converted into usable heating and cooling through thermochemical or thermo physical processes within thermally activated energy conversion systems. These systems are broadly categorized as follows:

Open Sorption Cycles (e.g., solid and liquid desiccant-based systems).

Closed Sorption Cycles (e.g., absorption and adsorption refrigeration).

Thermo-mechanical Systems (e.g., Rankine or Stirling-based systems).

MATERIALS AND METHODS

Solar Panel Design and Specifications

Each photovoltaic (PV) panel is rated based on its direct current (DC) output power. Commercially available panels currently achieve conversion efficiencies of up to 17.4%. Most standard PV panels produce 12V DC, although higher-output configurations (e.g., 24V or 48V DC) are commonly used in larger systems.

The electrical performance of solar panels is typically described by a set of standard parameters, including: Nominal Voltage, Maximum Power Voltage, Open-Circuit Voltage (Voc), Maximum Power Current (Imp), Short-Circuit Current (Isc), Maximum System Voltage, Rated Power Output.

Table 1 presents the technical specifications used in this study for the selected solar panels.

The maximum power output of a solar panel refers to the highest amount of electrical power it can deliver under optimal operating conditions, which in this case is rated at 100 watts. The maximum voltage is the highest voltage generated when the solar panel provides its rated output (17.9 volts). The open circuit voltage (Voc) of the solar panel is the highest voltage output of the solar panel when there is no load applied to it and thus it measures the highest voltage potential between two points without a current flowing through the panel. The maximum current refers to the highest current provided from the solar panel when all of its internal components are operating at full capacity while the short circuit current is

Table 1. Technical specification of solar panels.[12].

Parameter	Specification
Model	Sp20 125×125/4@36
Cell material	Monocrystalline
Maximum power (watts)	100watts
Cell grade (A,B,C,D)	A
Nominal voltage	12 V
Maximum power voltage (Vmp)	17.9 V
Open circuit voltage (Voc)	21.5 V
Maximum power current (Imp)	5.88 A
Short circuit current (Isc)	6.55 A
Maximum system voltage(vollts)	480 V
Cell efficiency	17%
Dimensions	Length: 120 mm, Width: 68 mm, Thickness: 35 mm
Weight	40 lbs
Cell size	125 × 125 / 4 mm
Cell quantity	176
Frame material	Extruded anodized heavy aluminum
Encapsulation	EVA
Rear side	DuPont Tedlar (TPT)
Glass thickness	3.2 mm
Maximum wind resistance	65 m/s (145 MPH)
Maximum hail resistance	1+ inch @ 50 mph
Maximum load capacity	200 kg/m²
Output tolerance	±3%
Temperature coefficient of Isc	−(0.10 ± 0.01) % / °C
Temperature coefficient of Voc	−(0.38 ± 0.01) % / °C
Temperature coefficient of power	−0.47 % / °C
Operating temperature range	−40 °C to +80 °C
Connection type	Waterproof junction box (customizable)
Power guarantee	90% within 10 years, 80% within 25 years
Glass type	Low-iron, high-transparency tempered glass
SLA battery voltage	

the amount of current present when the output terminals of the solar panel are shorted and therefore directly connected together without any resistive loads present between them; this short circuit current acts as a design and safety reference for solar power systems. Maximum system voltage is the voltage at which multiple solar panels can be connected in series for system design purposes, and when connecting solar panels in series, the maximum system voltage is 480 volts, so theoretically, a maximum of six solar panels can be connected in one group ((480/(4 × 17.9))≈6) if the total combined voltage remains within an acceptable level. When designing a solar energy system that will supply electricity to four water coolers, it is imperative to consider, analyze, and evaluate the important components of a solar energy system. This includes the photovoltaic panels, charge controllers, energy storage devices (batteries), and an inverter to convert the direct current (DC) output from the panels to alternating current (AC) for use with standard home and office electric loads. Fig. 2 shows the schematic diagram of the PVT solar system.

In this scenario, a subscriber intends to establish a solar-powered system operating at 12 volts direct current (DC) to support the continuous operation of a water cooler. The rated power consumption of the water cooler is 100 watts.

It is generally recommended that the charging current be approximately 10% of the battery's ampere-hour rating. Therefore:

Charging Current = 67 Ah × 10% = 6.7 A

Required Solar Panel Output = 6.7 A × 12 V = 80.4 W

Thus, a solar panel rated at 80–100 watts is appropriate. Since 100 W panels are commercially available and offer added reliability, they are the preferred choice.

The charge controller should be selected to accommodate both the system voltage and current. In this case:

Recommended Charge Controller = 12 V, 10 A

These calculations exclude system losses. To account for inefficiencies due to wiring, dust, temperature effects, and conversion losses, it is standard to include an additional 25% system loss margin in the final sizing.

Final System Components (Based on Market Availability and Practical Consideration): Solar Panel: 100 W, 12 V, Battery: 12 V, 100 Ah, Charge Controller: 12 V, 10 A.

Solar Panel Efficiency

The efficiency of a photovoltaic (PV) panel is determined by comparing the electrical output power to the solar energy input incident on the panel surface.

The input power from solar irradiance is typically considered as 1000 W/m² under standard

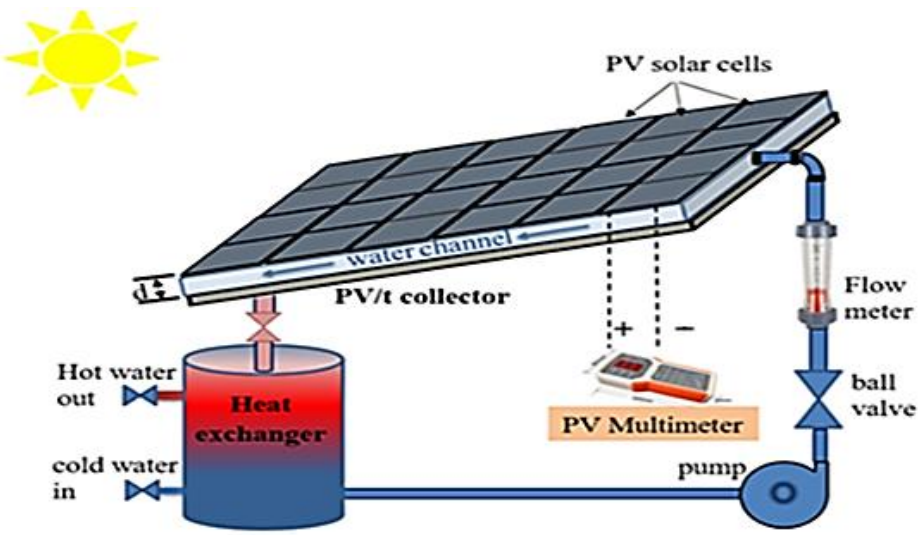

Fig. 2. Schematic diagram of the PVT solar system [12].

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test conditions. For instance, if a solar panel with an area of 1 m^2 generates 170 W, then its efficiency is:

Efficiency= (1701000) × 100=17%

This indicates that the panel converts 17% of the incident solar energy into usable electrical energy.

Fig. 3 presents the experimental setup of the solar energy system used in this study, which was installed on the rooftop.

Components of the Solar System

Solar Panel

The core component of any solar power system is the solar panel array, which serves the dual function of generating electrical energy and charging storage batteries. Solar panels are generally classified into three principal types, based on their material composition and manufacturing process.

The primary component of a photovoltaic power system is the solar panel (or array), which converts solar energy into electricity and supplies it to a storage system, typically a battery. Solar panels are generally classified into three main categories based on the structure and manufacturing method of the photovoltaic cells.

Monocrystalline Solar Panels

Monocrystalline panels are the most efficient and also the most expensive type commercially available. These panels are fabricated using high-purity silicon through a precise crystal-growth method known as the Czochralski process. This technique produces cylindrical silicon ingots, which are subsequently sliced into thin wafers—typically between 0.2 mm and 0.4 mm thick. The wafers are then photovoltaic (PV) cells and interconnected to form a complete solar module. Fig. 4 illustrates the monocrystalline solar panel

Fig. 3. Experimental design of solar system.

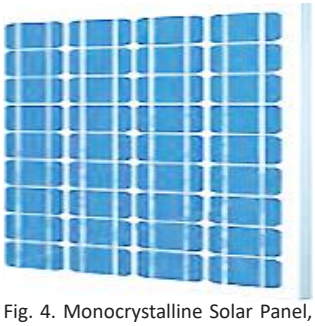

Fig. 4. Monocrystalline Solar Panel, 12 Volt, 100 Watt.

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employed in this research.

Polycrystalline Solar Panels

Polycrystalline solar cells—sometimes called multicrystalline panels—are cheaper to produce than monocrystalline solar cells, although they have a slightly lower efficiency than their monocrystalline counterparts. Polycrystalline solar cells are not made from a single crystal of silicon but rather from many small crystals that were melted together and then cut into wafers before being assembled into PV cells and connected to create a full-size solar panel. The result of this process is the typical speckled or fractured texture of polycrystalline panels, which some people liken to shattered glass.

Amorphous (Thin-Film) Solar Panels

Unlike crystalline solar panel systems, the composition of amorphous (thin film) solar cell technology is based on an extremely thin film of silicon that is coated onto a support material like glass, metal, or plastic instead of creating large solid blocks of crystalline material. While amorphous solar panel technology produces far less total energy conversion than crystalline technologies, producing an equivalent amount of electricity requires substantially more (i.e., a greater) area of amorphous solar cell compared to crystalline solar cell technology. Nevertheless, due to the nature of their construction, they can be made in continuous strips of material, making them perfect for being incorporated into construction materials such as solar roofing for large southern-facing roofs.

Charge Controller

Controller chargers are an essential part of a photovoltaic (PV) power system as their function is to regulate the charging process of PV batteries. Effective management of the charging cycle helps prevent damage associated with overcharging as well as increasing battery lifespan (thus increasing the usability of the battery) and improving overall system efficiency. The reason that we need charge controllers is that solar cells produce high-voltage outputs when exposed to direct sunlight, which can produce voltages that are excessive for the safety of batteries. Therefore, the main function of a charge controller is to monitor the voltage from the solar arrays and to adjust the amount of energy being sent to the batteries based on the input voltage variability.

Inverters

As one of the most important components of a solar energy system, the Power Inverter has two primary purposes: (1) to convert the 12-Volt DC in the battery bank into 220-Volt AC so that standard electrical devices can be operated, and (2) when connected to an external AC source (like a generator or the Electric Utility Grid), it will enable the batteries to be recharged.

Fig. 5. Charge Controller.

Fig. 6. Inverters.

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Storage Batteries

Storage batteries retain electrical energy through electrochemical reactions. Appropriate wiring and cables are utilized to interconnect the various components of the experimental setup, ensuring safe and efficient power transmission.

Connecting the Charge Controller

We need to use the appropriate size of wire when connecting PV arrays to the input terminal of your charge controller. The current through the battery cables connected to the charge controller will not exceed the current through the PV array, so we should use the same gauge of wire for these connections. The charge controller's output terminals are typically located near the batteries; therefore, using the same size wire as used for the input from the solar panel will minimize voltage drop in the system and improve overall performance

Connecting the Power Inverter

The final component_of the system is the power inverter. Due to the high current draw during operation of both systems (inverter and battery bank), both the inverter and battery bank require the largest diameter wire that will fit into the system. An inverter's AC power supply can take a considerable amount of amperage from the battery, thereby requiring that these two components (inverter and battery bank) be connected with heavy gauge wire that ideally will be less than six feet in length to minimise the power losses that would occur. The size of these cables is similar to the size of automotive battery cable. For example, an AC appliance drawing 10 Amps will draw approximately 100 Amps from the battery system at 12 volts DC.

Connecting the Batteries

The batteries are the energy storage component of any installed system and are connected to the remaining components in a way like a vehicle battery. Therefore, their installation requires the use of robust, heavy-duty, high-amperage cables capable of safely transmitting current to and from all devices, as well as handling the full charging capacity of the entire battery bank. The use of heavy-duty cables ensures a secure, efficient, and durable electrical connection between the batteries and the associated equipment. For proper wiring arrangements, standard battery wiring diagrams should be consulted, illustrating both series and parallel connections. By applying these configurations, a battery bank can be designed to operate at 2, 4, 6, or 12 volts, depending on the specific requirements of the system.

Parallel Wiring to Increase Current (Power)

Fig. 8 illustrates the parallel wiring configuration

Fig. 7. Batteries.

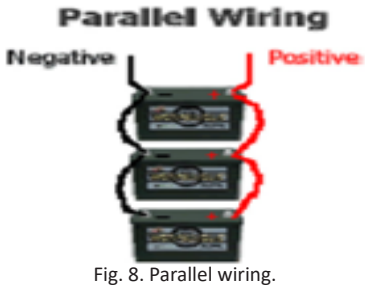

Fig. 8. Parallel wiring.

of a battery bank.

As displayed above, the diagram demonstrates the configuration of a parallel circuit, which allows the electrical current capacity or power output to be increased from the set of battery banks. An example of this would be if we had 12-volt batteries. Therefore, if we connect three 12-volt batteries in parallel, we have effectively created a 12-volt battery with three times more energy than a single battery while keeping the same voltage (12 volts). This type of wiring will give us much more current at a voltage of 12 volts. Jump-starting a car is a well-known real-life situation where parallel-wired systems are employed to provide a higher current when beginning another vehicle.

Series Wiring for Increasing Voltage

Fig. 9 shows the series wiring configuration used to increase system voltage.

The diagram shows a hybrid wiring method, which combines series and parallel connections, to increase the current capacity of the electric vehicle's battery bank and the voltage capacity. In the example shown, 12-volt batteries are used. When we connect two 12-volt batteries in series, we will have a voltage of 24 volts. This is done three times to create three separate 24-volt strings of batteries. The three strings of batteries are connected in parallel to create one large, high-capacity 24-volt battery system. This method creates double the voltage of a single 12-volt battery, and three times the current (or the total electric power) due to the parallel configuration of the three series-connected groups [12].

Enclosure (Container)

Protective housing of batteries and Controllers is required for the protection of the components against Physical Damage, Environmental Conditions, and Contaminants; Additionally, providing additional protection will contribute to the extended Operational Life and Increased Reliability of the components making up the overall solar Energy Collection System [13,14].

RESULTS AND DISCUSSION

Fig. 11 illustrates the variation in hourly efficiency of the solar-powered cooling system when operated with six solar panels and eight solar panels throughout the day. The results

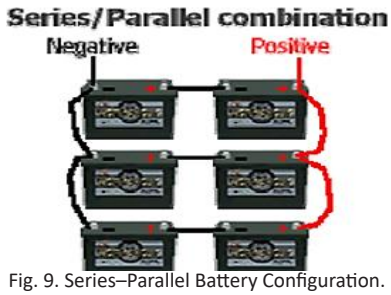

Fig. 9. Series–Parallel Battery Configuration.

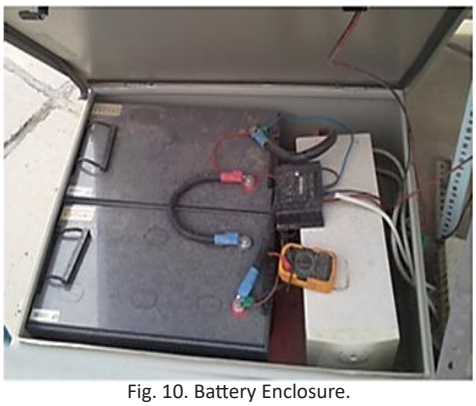

Fig. 10. Battery Enclosure.

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indicate that the efficiency of both configurations changes according to solar radiation intensity and ambient weather conditions. During the early morning hours, the efficiencies of the two systems are relatively low because solar irradiance is limited, resulting in reduced electrical power generation. As solar radiation increases toward midday, the efficiency of both configurations gradually improves due to the higher photovoltaic output. The system equipped with eight solar panels generally exhibits higher efficiency values compared with the six-panel configuration because of its greater energy production capacity. Around noon, when solar irradiance reaches its maximum level, both systems achieve their peak efficiencies. The eight-panel arrangement maintains a more stable performance during periods of high cooling demand, providing sufficient electrical energy to operate the cooling components effectively. In contrast, the six-panel system may experience

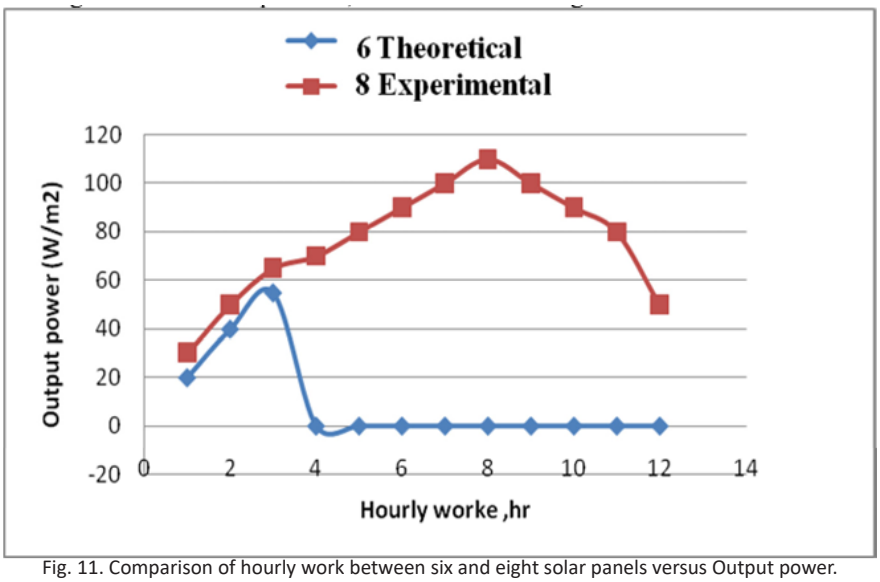

Fig. 11. Comparison of hourly work between six and eight solar panels versus Output power.

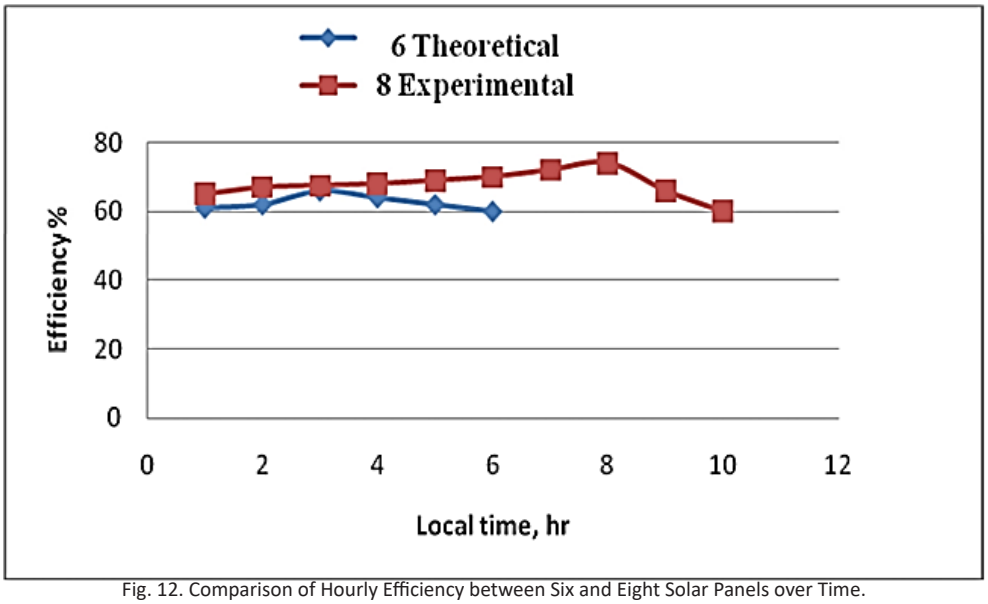

Fig. 12. Comparison of Hourly Efficiency between Six and Eight Solar Panels over Time.

slight fluctuations in efficiency due to limited power availability. During the afternoon hours, the efficiency of both systems begins to decrease as solar radiation declines. However, the eight-panel configuration continues to demonstrate better operational stability and higher overall efficiency. The comparison highlights the positive impact of increasing the number of photovoltaic panels on system performance. The additional panels enhance energy generation, reduce power shortages, and improve the overall effectiveness of the cooling system. Therefore, the eight-panel configuration can be considered a more reliable and efficient option for sustaining cooling performance under varying solar conditions throughout the day.

The efficiency of the solar panels is analyzed and depicted in Fig. 12. The experimental results show that the maximum panel efficiency reaches approximately 78% at the eighth hour of operation when using eight solar panels. In contrast, the efficiency peaks at around 64% at the third hour during the experimental operation with six panels [15].

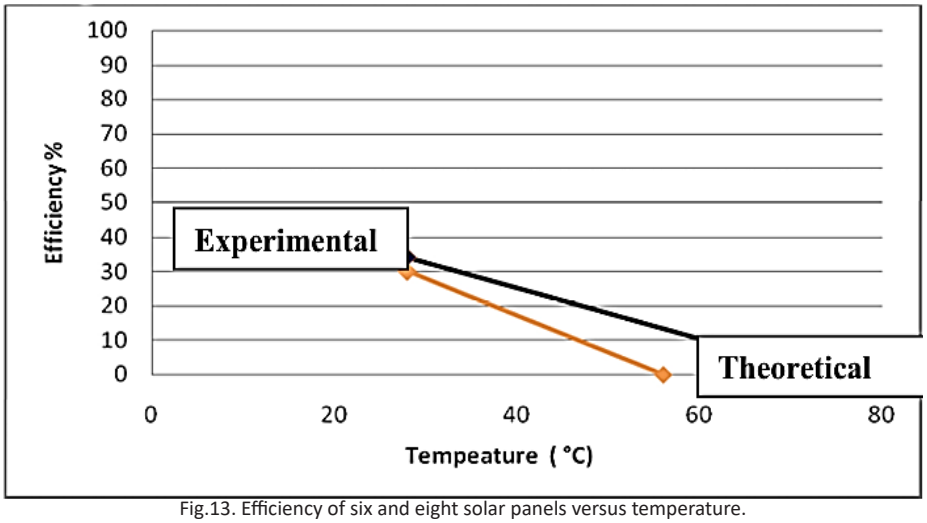

Fig.13. Efficiency of six and eight solar panels versus temperature.

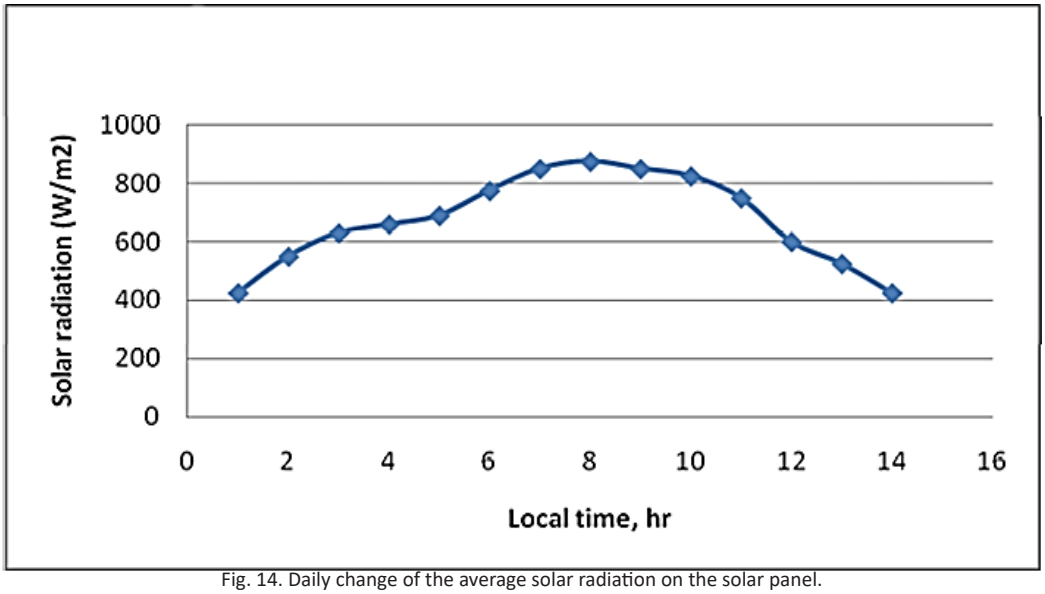

Fig. 14. Daily change of the average solar radiation on the solar panel.

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Fig. 13 shows how the efficiency of solar panels changes with temperature for two different systems: one with six panels and another with eight panels. The graph clearly indicates that as the temperature rises, the efficiency of both systems decreases. This happens because higher temperatures reduce the voltage output of photovoltaic cells, which directly lowers their efficiency. The eight-panel system consistently performs better than the six-panel system across the temperature range, suggesting that adding more panels can help compensate for losses caused by heat. The drop in efficiency becomes more noticeable at temperatures above 45°C, highlighting that thermal effects are a significant factor in solar panel performance. This also implies that cooling strategies, such as passive airflow or heat sinks, could improve the overall energy output of the panels [16].

Fig. 14 shows the daily variation of average solar radiation on the panels. The radiation increases gradually in the morning, reaches a peak around midday, and then decreases in the afternoon, forming a typical bell-shaped curve. This pattern reflects the natural movement of the sun and the intensity of solar energy available during the day. Comparing this to Fig. 13, it is evident that peak solar radiation does not always correspond to peak panel efficiency because high temperatures at midday can reduce efficiency even when sunlight is strongest. Therefore, the actual energy generated depends on both solar intensity and temperature. Understanding this daily variation is crucial for designing solar-powered cooling systems, as it helps determine the optimal panel size, orientation, and the need for energy storage to maintain a stable cooling performance throughout the day [17].

CONCLUSION

This study presented a theoretical and experimental investigation of utilizing solar energy to power a water cooling system. The results demonstrated that photovoltaic technology can effectively provide the electrical energy required for cooling applications while reducing dependence on conventional energy sources. The theoretical calculations were found to be in good agreement with the experimental measurements, confirming the validity of the proposed system design. The experimental analysis showed that solar panels were capable of generating sufficient power to operate the cooling system during periods of high solar irradiance. System performance was strongly influenced by solar radiation intensity, ambient temperature, and the number of installed photovoltaic panels. Increasing the number of solar panels improved energy production and enhanced overall cooling efficiency. The configuration employing eight solar panels exhibited better performance and greater operational stability than the six-panel configuration. The cooling system successfully reduced water temperature and maintained effective operation throughout the testing period. The findings also revealed that solar-powered cooling systems offer significant environmental benefits by reducing greenhouse gas emissions and fossil fuel consumption. Furthermore, the proposed system can be considered a sustainable and economically viable solution for regions with abundant solar resources. The study confirms the feasibility of integrating renewable energy technologies into water cooling applications. Overall, solar energy represents a reliable alternative energy source for powering cooling systems, contributing to improved energy sustainability and environmental protection.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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