An Advanced Cooling Device for Concentrated Photovoltaic Systems

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***Abstract*—Concentrated photovoltaics (CPV) have the potential to significantly enhance the energy conversion utilization of solar panels and reduce solar generation costs, making them a crucial area of advancement in solar power generation technology. However, the concentration of sunlight can lead to overheating of solar panels, resulting in a notable reduction in both the efficiency of solar power generation and the lifespan of the panels. This challenge remains the predominant technical hurdle that hinders the application of concentrated photovoltaic power generation technology. In this study, we propose a new cooling method for concentrated photovoltaic power generation systems via an integrated approach of incorporating Phase-Change Thermal Storage (PCTS) and Thermoelectric Generator (TEG) technology. This new method not only enhances the overall system's electricity generation efficiency but also effectively resolves the technical challenge of concentrated photovoltaic panel overheating issues, ensuring the continuity of concentrated photovoltaic power generation and extending the lifespan of solar panels and their components. In order to make full use of the wasted heat generated by photovoltaic power generation and effectively improve the power generation efficiency of the system, this work developed a phase change heat storage device based on a phase change material. This device uses the temperature difference between day and night to recover wasted heat from photovoltaic power generation. Through integration with the thermoelectric power generation system, thermal energy can be converted into electrical energy. In addition, the Peltier effect of thermoelectric materials is used to construct a photovoltaic panel overheating protection system, which significantly improves the reliability and service life of the system.**

***Keywords*—Concentrated Photovoltaics (CPV)， Phase-Change Thermal Storage (PCTS)，Overheating Protection, Photovoltaic Efficiency, Thermoelectric Generator (TEG).**

I. INTRODUCTION

With the development of the economy, the world's energy consumption will continue to grow. Carbon dioxide emissions will remain at high levels for a certain period until the trend is reversed. Achieving carbon neutrality and reducing greenhouse gas emissions are pressing challenges that need to be addressed urgently. Carbon neutrality is crucial for mitigating the impacts of climate change, necessitating transitions to sustainable energy development and transportation electrification. In order to achieve sustainable development and green mobility, including electric vehicles, the proportion of renewable energy sources, with solar energy as a representative, in the primary energy mix will continue to increase. Solar energy reaching the Earth's surface has a power output of approximately 800 trillion kW, equivalent to the heat released by burning 5 million tons of coal every second [1]. The utilization of solar energy is widely recognized as the most promising avenue to address energy and environmental concerns, and it has received high attention and experienced rapid growth. Seeking high-performance photovoltaic technology has become a global consensus in the development of energy technology.

Among various photovoltaic technologies, concentrated photovoltaics (CPV) are highly sought after due to their potential for significantly boosting solar energy panel utilization and reducing generation costs [2, 3]. They are considered a pivotal direction in the advancement of solar power generation technology [4]. However, the concentration of sunlight in concentrated photovoltaics generates substantial heat, leading to an elevated temperature that reduces the photovoltaic cells' photovoltaic conversion efficiency, causes component aging and cracking, and even poses safety risks. The risks include spontaneous combustion, which directly threatens the security of the entire power generation system. The overheating issue severely constrains the application and widespread adoption of concentrated photovoltaic power generation technology. Therefore, there is an urgent need for the development of innovative cooling and protection systems for concentrated photovoltaics. These systems should not only effectively prevent overheating accidents in solar panels but also maintain the power generation system at the appropriate operating temperature, thereby significantly improving the system's electricity generation efficiency.

The temperature effect on solar cells indicates the loss of photovoltaic (PV) efficiency and energy yield due to the increase of the panel temperature. The significant temperature rise of the PV panel under different operating conditions has been extensively investigated. It is worth mentioning that solar cells under intensive solar radiation have a panel temperature of 50–70 °C, leading to an efficiency loss of 10–25%. Furthermore, once a cell reaches its upper-temperature limit, an increase of 10°C in temperature leads to a doubling of the aging rate for crystalline silicon cells [5]. To address the challenge, various cooling methods for solar cells have been developed. Common cooling strategies for solar cells include passive cooling, phase change materials (PCMs) based thermal energy storage, and active cooling [6]. Various passive cooling methods have been employed for photovoltaic cells, including air cooling, liquid cooling, evaporative cooling, radiative cooling, and liquid cooling [7]. Regarding cooling efficiency, methods like air cooling, radiative cooling, and thermoelectric cooling, have relatively high thermal resistance between the cells and the environment, leading to unsatisfactory cooling results. On the other hand, liquid cooling, evaporative cooling, and phase-change material cooling reduce thermal resistance between the cells and the environment by roughly an order of magnitude compared to air cooling. When considering device complexity, air cooling stands out among traditional cooling methods for its simplicity and straightforward maintenance. Liquid cooling, while effective in terms of cooling, involves a more complex structure and higher costs. Hybrid cooling methods or adopting non-electrically driven techniques can further enhance the heat dissipation of PV panels and improve system efficiency.

Semiconductor thermoelectric (TE) technology has evolved based on the Seebeck effect. In recent years, a novel composite solar power generation technology, combining photovoltaic and thermoelectric power generation (referred to as PV-TE), has gained widespread attention from scholars worldwide. A. Rezania et al. have integrated thermoelectric conversion with photovoltaic conversion and conducted performance analysis on simplified PV-TE systems. The results indicate that the Z in the quality factor (ZT) is equal to 0.004 (corresponding to Bi_2Te_3), while T represents the ambient temperature K. Numerical simulations demonstrate that variations in K do not provide significant advantages to the water-cooled concentrating photovoltaic-thermoelectric (PV-TE) system, primarily due to the low efficiency of thermoelectric power generation [8]. PV-TE systems need to carefully consider the impact of changing environmental conditions on the performance of power generation devices. Furthermore, for the cold side of thermoelectric power generation devices, typically, no cooling devices are installed, and air cooling with added fins or environmental temperature is used, which does not provide ideal cooling results [10].

Stropnik conducted simulations on two PV panels using the TRNSYS software suite, followed by a comparative analysis between the simulated outputs and actual experimental data [11]. The findings from this comparison revealed a significant thermal performance differentiation: over the course of a single day: the maximum surface temperature differential of the PV panel without PCM integration exceeded that of its PCM-integrated counterpart by 35.6°C. Further calculations were performed within TRNSYS to quantify the maximum and average enhancements in electrical efficiency attributable to the incorporation of PCM into the PV panels. The culminating simulation results indicated a noteworthy enhancement in the annual electricity generation capacity of the PV-PCM panels situated in Ljubljana, showcasing an increase of 7.3% [11]. Further research in areas such as thermoelectric materials and the optimization of system design remains imperative to enhance efficiency and mitigate costs within integrated energy systems. For instance, utilizing high-performance nanomaterials and employing concentrating devices can enhance system efficiency. Chen et al. have analyzed the impact of heat sinks on PV-TE power generation systems, suggesting that using water cooling can yield higher output power while liquid cooling has certain drawbacks, as previously reviewed [12].

This paper proposes a PCM and TEG based, efficient, energy-saving, and stable automatic temperature control cooling system for concentrated PV panels. By utilizing eco-friendly, low-cost, phase-change heat storage temperature control technology, we aim to replace the conventional, large external energy-dependent circulating cooling methods (such as liquid circulation cooling) using ambient temperature as the cold side temperature or employing air cooling with added fins for thermoelectric power generation devices. By leveraging waste heat for secondary electricity generation and enhancing heat dissipation to improve electricity generation efficiency, the proposed method can reduce costs, improve the system's durability, and enhance the overall economic benefits.

II. The PV-TEG System Under Stuy

The cooling system mainly consists of a TEG, a phase-change heat storage (PCHS) unit, and a semiconductor temperature control protection device, which is mounted on a support frame. The concentrator plates and the hybrid power generation host are shown in Fig. 1 and Fig. 9 (later in the paper). The host and concentrator plates are connected by a rotating axis, allowing for the adjustment of the concentration angle, effectively focusing the light source.

The coupled PV-TE (photovoltaic thermoelectric) system mainly consists of monocrystalline silicon solar panels, a set of eight 40x40 mm thermoelectric modules for thermoelectric power generation, PCM, temperature sensors, diodes, and batteries. The base layer of the system is a 350mm×220mm solar panel, which is bonded to the main body using thermally conductive silver silicone grease, as shown in Fig. 2.

Fig. 1(a). Device main body (top).

Fig. 1(b). Device main body (bottom).

Fig. 1(c). The TEG and phase-change heat semiconductor temperature control protection (front).

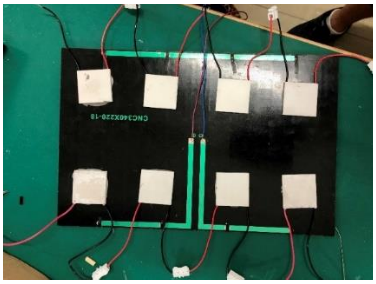

Fig. 1. The PV-TE temperature control host back structure (temperature difference power generation part).

This layer can be heated to approximately 90-100°C when exposed to sunlight and subsequently generates electricity, serving as the hot side of the thermoelectric modules. The modules are arranged in a 4×2 array on the back side of the solar panels. The other end of the thermoelectric module is connected to the PCM, which is contained within a thermally conductive copper box to maintain the temperature around 35°C, thus establishing the cold side of the modules. Thermal silver silicone grease promotes this interface, allowing the temperature difference to be used for secondary power generation.

The resistance of the thermoelectric module increases linearly as the temperature increases. The greater the temperature difference, the higher the resistance, as shown in Fig. 3(a) [13]. When maintaining a temperature difference of about 30°C, between 40-80°C, the thermoelectric module will output stably, as shown in Figure 3(b) [13].

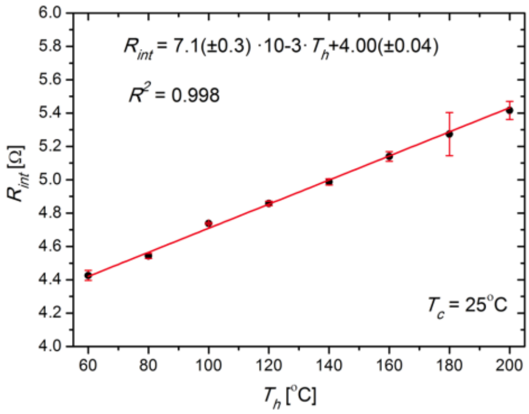

Fig. 3(a). Internal resistivity (R_{int}) as a function of T_h, for T_c = 25°C [13].

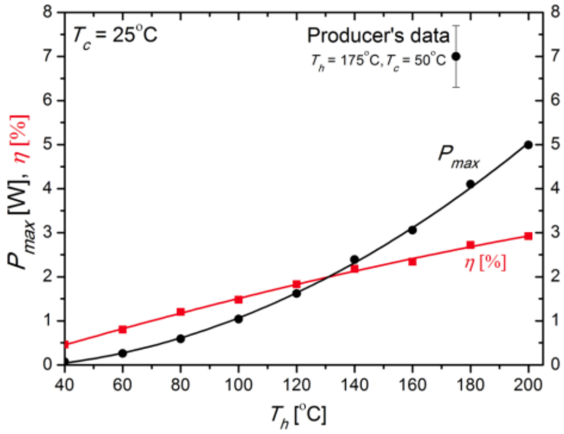

Fig. 3(b). Maximum efficiency (η) and maximum power (P_{max}) as a function of Th, Tc = 25°C [13].

The TEG efficiency can reach 1.4%~2% at medium and low temperatures, respectively [13]. The upper limit of the operating temperature of the low-temperature thermoelectric module is 250 °C, and the power generation output is proportional to the temperature difference. When working, the device can maintain a stable temperature difference between 40°C and 80°C and continuously provide a DC current to the battery.

III. Phase-Change Thermal Storage and Thermoelectric Generator Based Cooling System

The high residual heat generated by solar concentration is utilized for secondary thermoelectric generation, with the produced electrical energy being stored for subsequent use. The PCM, $Na_2SO_4.10H_2O$, is positioned at the cold end of the thermoelectric generation module, shown in Fig. 4. As its temperature rises, the solid $Na_2SO_4.10H_2O$ transitions to a liquid state, absorbing the heat from the cold side of the thermoelectric module during the phase change reaction, thus maintaining a stable environment for thermoelectric generation. When the ambient temperature at night falls below the melting point of $Na_2SO_4.10H_2O$, the heat absorbed during the day is released, creating a cooling cycle system that operates without the need for external energy supply, as shown in Fig. 5.

Fig. 4. The phase change material, Na2SO4.10H2O.

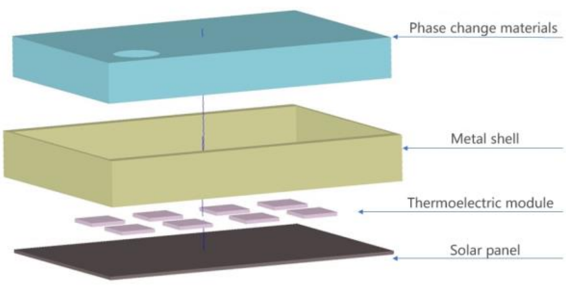

Fig. 5. Host Structure.

When the heat produced by concentration exceeds the rated operating temperature of the solar panels, the temperature control system will kick in, switching the operational mode of the thermoelectric modules. Under this mode, the stored electrical energy is used to power the thermoelectric modules to cool the PV panels through the Peltier effect, in which an exchange of heat occurs between the cold and hot ends of the modules. This process effectively safeguards the PV generating units and the main system components from damage due to overheating.

IV. Experiment and Results

Prior to conducting the experiment, we developed a three-dimensional (3D) model of the experimental apparatus and performed thermodynamic simulations to ensure that the thermoelectric modules maintain a stable temperature differential during the operation of the device, thereby facilitating the secondary electricity generation, as shown in Fig. 6.

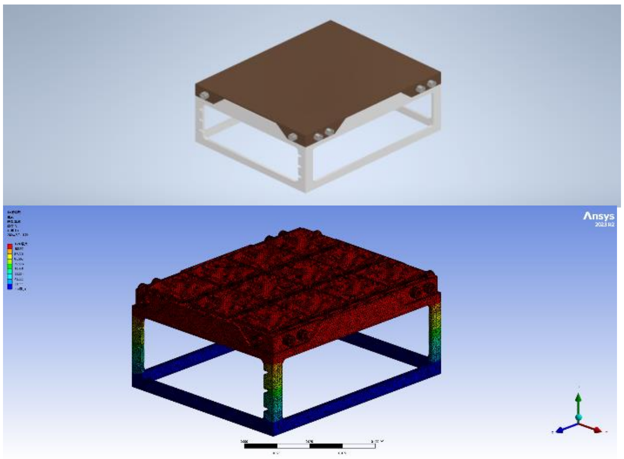

Fig. 6. CPV main body thermodynamic simulations.

A. *Coupled PV-TE Host*

The Coupled PV-TE host mainly consists of a monocrystalline silicon solar panel, eight pieces of 40x40 mm thermoelectric modules for thermoelectric power generation, a phase-change heat storage material primarily composed of $Na_2SO_4.10H_2O$, temperature sensors, diodes, and a battery, as shown in Fig. 7.

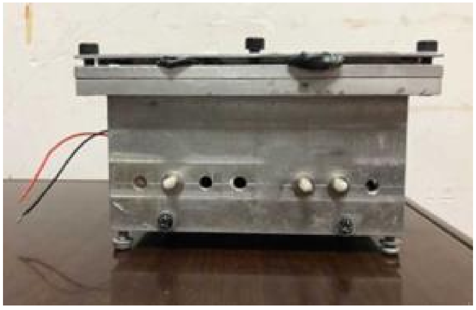

Fig. 7(a). The prototype of the PV-TE system.

Fig. 7(b.) Inside the temperature control system.

B. *Automatic Temperature Control and Protection System*

The automatic temperature control and protection device structure includes a battery, a thermoelectric module assembly, a solar panel, two diodes, a normally open (NO) and normally closed (NC) 100°C temperature control switch, and wires. The device circuit is shown in Figure 8. When the concentrated temperature becomes too high (exceeding 100°C), a unidirectional charging transmission line, consisting of diodes and a 100°C normally closed temperature control switch, switches to the output line. This provides reverse power to the thermoelectric power generation assembly, utilizing the Seebeck effect to lower the temperature at the hot end. This process serves to protect the solar panel and other components from damage. Once the hot end temperature decreases, the above process is repeated, achieving energy efficiency, environmental friendliness, and safety benefits.

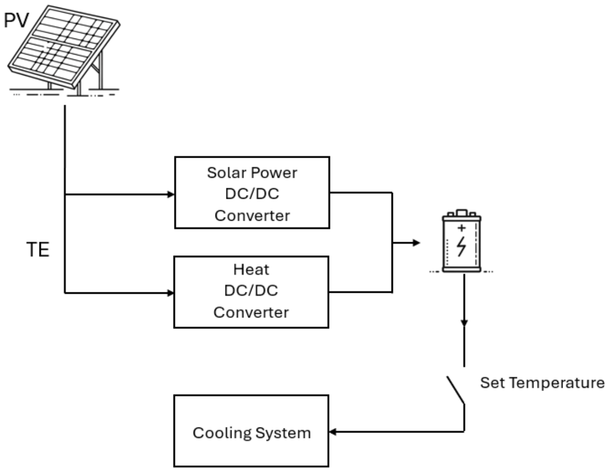

Fig. 8. Temperature Control Circuit.

C. *Concentrating/Reflecting Plates*

The concentrator/reflector plates are made of highly durable and corrosion-resistant 2205 stainless steel, with a width of 350mm and a length of 1900mm. They employ a trough-style concentration pattern with a curvature in the form of a hyperbolic function.

$$f_{(x)} = -\sqrt{1 + \frac{x^2}{N^2 - 1}}$$

In the design of our concentrating/reflecting plates, corresponding to the above formula x represents the position on the reflector, which affects the local value of the curvature; and N is the curvature characteristic parameter that affects the entire reflector.

The parallel light incidents on the concentrator plate are reflected and focused on the focal point of the hyperbola. The host is positioned 200mm below the focal point of the hyperbola, creating a rectangular light spot of 350mm×220mm on the solar panel. This arrangement covers the entire solar panel to maximize efficiency and utilization, as shown in Fig. 9.

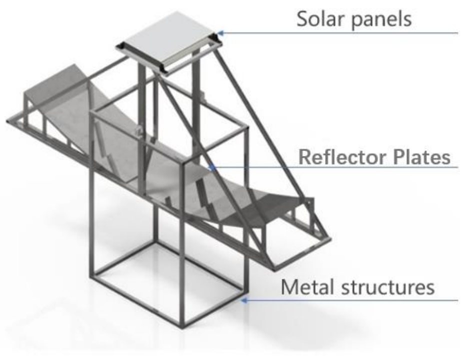

Fig. 9 (a). Overall structure of the concentrated PV system.

Fig. 9 (b). A prototype of the concentrated PV system.

D. Bracket

The bracket is constructed using low-cost, lightweight, and easy-to-disassemble industrial European standard 2020 and 2040 aluminum profiles. The structural dimension is 600mm×420mm×1000mm.

E. Circuit Control System

As shown in Fig. 8, DC-DC converters play a pivotal role in solar power systems. They not only maximize the energy extracted from the solar panels but also ensure the system's stable, reliable, and efficient operation with the following main functions and features:

Voltage Regulation: The output voltage of solar panels can vary with changes in irradiance and temperature. DC-DC converters can adjust this voltage to a constant predetermined value suitable for other system components.

Battery Charging Management: In solar storage systems, DC-DC converters can act as charge controllers for the batteries, ensuring they are charged and discharged under optimal conditions.

Management of Series and Parallel Modules: When multiple solar panels are connected in series or parallel, DC-DC converters ensure that each panel operates at its optimal working point.

Enhancing System Efficiency: By employing efficient switching techniques and advanced control strategies in the converter, energy losses can be minimized, thus improving the efficiency of the entire system.

F. Experimental Studies

Experimental studies have been carried out to compare the proposed cooling system with a traditional natural cooling method. Fig. 10 shows the comparison result of cooling 500 ml of hot water under an ambient temperature of 19 °C. The result shows that the proposed cooling system has a superior cooling performance.

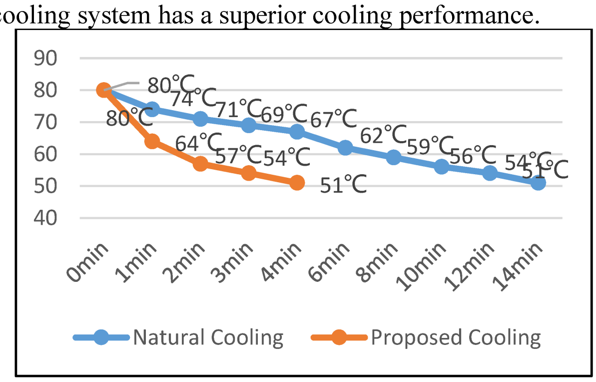

Fig. 10. Comparison of the proposed cooling method with the natural cooling method.

Based on the information provided by CPV and TEG manufacturers, it can be estimated that the proposed cooling system can enhance the overall power generation efficiency from 1.4% to 2%, while extending the lifespan of the power generation equipment by 5 to 10 years and reducing the investment cost of concentrated photovoltaic cooling equipment by an average of 70 to 150 dollars per square meter.

V. Conclusion

The proposed phase change material based cooling method can maintain both solar panels and thermoelectric modules within a preferable temperature range, which extends the equipment's operational life, improves energy efficiency, facilitates secondary electricity generation via the thermoelectric modules, and enhances the safety of the whole system. Compared to the existing cooling methods currently used for concentrated photovoltaic panels, such as air cooling and water cooling, the phase change thermal storage material offers better stability and lower costs. Experimental studies have been conducted and validated the superior performance of the proposed cooling system over conventional cooling methods.

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