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To cite this article: Yong-Kwon Kang *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 042011

Journal of Physics: Conference Series **2600** (2023) 042011 doi:10.1088/1742-6596/2600/4/042011

Optimization of Building integrated photovoltaic and thermoelectric hybrid energy harvesting system for different climatic regions

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Abstract. As energy saving emerges as a critical factor for the sustainable development of humankind, the importance of Zero-Energy Buildings (ZEB) is gradually increasing. Therefore, much research is being conducted on high-efficiency renewable energy technologies that can be applied in urban areas. However, increasing the efficiency of BIPV were proposed and studied because of the need for the renewable energy source. Such as using phase change material (PCM), heat fin, wavelength selection, PV surface temperature decreasing or using a thermoelectric generator (TEG), and convection cooling utilizing the waste heat from the PV. In most previous studies, the performance when each method was analyzed through experiments or simulations. However, the design analysis for maximum performance still needs to be conducted. Therefore, a BIPV combined with a PCM and TEG (BIPV-TEG-PCM) design is analyzed in this study. Herein, the three variables (phase change temperature of the PCM, heat fin spacing in the PCM container, and TEG arrangement) were analyzed through computational fluid dynamics (CFD)-based simulations. Moreover, through multi-objective optimization, the BIPV-TEG-PCM system of the optimal design was derived. Analysis results of the appropriate melting temperature of PCM, heat fin interval, and arrangement of TEG for the proposed system are 40 °C, 12.4 mm, and 187 mm, respectively.

1. Introduction

Because of urbanization, the increasing number of people living in cities has led to building more buildings [1]. In addition, more and more electronic devices are being used in buildings, such as internet of things (IoT) sensors, electric vehicles, air conditioning (HVAC) systems, Etc. Therefore, to obtain such a large amount of electric energy consumption in an environmentally friendly way, many studies are being conducted on applying renewable energy to cities. The most widely used system is photovoltaic (PV) panels. Nevertheless, the reality is that it is challenging to supply a large amount of renewable energy due to cities' limited space and renewable energy. Therefore, many studies have been conducted on increasing the efficiency of the PV panel.

However, unlike conventional PVs, BIPVs are fixed to the wall or roof of the building. Therefore, BIPVs have a limiting time and angle of receiving sunlight and reduced generation efficiency of PV panels due to a lack of heat rejection. The temperature of the PV panel directly affects the PV efficiency; When the PV cell temperature increases, the power generation efficiency decreases by 0.4 or 0.65% per ℃ [2]. In addition, when the panel surface temperature reaches 65 ℃, the power generation efficiency can be lowered to about 2.6% [3]. Therefore, to solve this problem, various methods to prevent the temperature rise of the PV cell have been studied. According to the heat transfer method, the cooling technology of PV panels can be classified into three types: convection, conduction, and radiation. In general, it has been proposed that a panel cooling system utilizes convection and conduction. Among the variable cooling technologies, liquid convection cooling showed the highest efficiency improvement at 22%, with phase change materials up to 21.2%, air convection cooling by 20%, and radiation cooling by up to 2.6%, that the efficiency of the PV panel was improved [4].

Therefore, many convection heat rejection solutions have been proposed to improve the efficiency of BIPVs. Koyunbaba et al. proposed an air-cooled-type BIPV thermal (BIPVT) system with a Trombe wall system. The experiments and computational fluid dynamics (CFD) calculations analysis results showed that the average electrical and thermal efficiencies of this system could reach 4.52% and 27.2%, respectively. Kaiser et al. studied a BIPV module system in a forced convection condition. This study experimentally analyzed the influence of the air gap size and the forced convection ventilation system. Under a duct velocity of 6 m/s, the power generation increased by 19% relative to the natural ventilation case [5]. In addition, some studies focused on water-cooling BIPVT systems. Kim et al. experimentally analyzed the energy performance of a water-cooled BIPVT integrated on a roof. According to the experimental results, it was found that the average thermal and electrical efficiencies were improved in the BIPVT are 30% and 17%, respectively [6].

However, there are disadvantages in that additional power sources are required (e.g., pump, valve), and the system becomes complicated using a fluid. In addition, most solar heat removed from the PV is discharged back to the outside air of the city; therefore, it increases the urban heat island effect.

In the case of BIPV, installation and maintenance are more complex than conventional PV panels because it is installed on the exterior of a building. Therefore, using fluid is difficult to apply because using fluid is easy to cause a problem such as a leakage. Therefore, research was conducted on the BIPV system using a phase change material (PCM) and thermoelectric generator (TEG) to increase efficiency via a passive method. According to previous research, using the PCM is an efficient passive cooling method for the PV panel [7–11]. Hasan et al. experimentally and numerically analyzed the PV-PCM system in a hot climate. It was found that PCM can decrease the PV panel by 13℃ at peak time, and its average energy efficiency increased by 5.9% relative to that of an existing panel combined with PCMs every year [12]. Sharma et al. analyze the paraffin wax on the Building-Integrated Concentrated Photovoltaic (BICPV) system. The lap-scale experiment was conducted to examine the cooling effect of PCM under the different levels of xenon lamp irradiation (500, 750, and 1200 W/m2). The experiment results show that the electrical efficiency increased by 1.15, 4.2, and 6.8%, respectively, and the PV panel surface temperature reduced to 3.8 ℃ [13]. Stropnik and Stritih experimental and simulation using TRNSYS software analyzed how much the PV panel efficiency increased with a PCM. The experimental results show that the PV with PCM can maintain the PV panel temperature low 35.6 ℃ than the PV panel without the PCM, and annually can produce electricity higher by 7.3% [14].

Moreover, the research showed that the PV-TEG hybrid system could increase efficiency by 1–16% compared with the conventional PV panel system. Makki proposed a heat-pipe-assisted PV-TEG hybrid system and investigated it numerically and experimentally. This study shows that further development of approximately 5% overall system efficiency was possible using a TEG [15]. In addition, Cotfas et al. analyzed the three types of TEG material for the PV-TEG hybrid system. Finally, the simulation results show that the PV-TEG hybrid system can produce more electric power by approximately 7% and increase the overall system efficiency by 18.93% than the conventional PV panel [16].

In the proposed PV-TEG hybrid system in previous studies, a cooling source is required, like air, water, Etc., on the cold side of the TEG. However, most convection methods require additional power sources to circulate the fluids. Darkwa et al. analyzed the PV-TEG-PCM system numerically and experimentally. The results showed that the PV-TEG-PCM system could achieve more than 9.5% electric power output than the standalone PV and PV-TEG hybrid systems [3]. Ko and Jeong suggest the BIPV-TEG-PCM system and analyze the power generation performance of the proposed system. The proposed system can generate 3.05 kWh from the TEG per year and generation improvements of 0.91%, -1.32%, 2.25%, and 3.16% from spring to the winter season, respectively [17].

In preceding studies, only the possibility and energy performance analysis of a system combining PV, TEG, and PCM were conducted. However, previous research on an appropriate design for maximum efficiency still needs to be completed. Therefore, the numerical analysis was conducted to find the optimal design manufacture of the proposed BIPV-TEG-PCM, which uses the micro capsulated phase change material (mPCM) to harvest solar/thermal energy wasted from the building envelope.

2. System overview

In this research, a simulation was conducted to model the surface temperature of Building-Integrated Photovoltaic-Thermoelectric Generator-Phase Change Material (BIPV-TEG-PCM) panels. The simulation employed finite volume discretization within the framework of computational fluid dynamics (CFD) using ANSYS Fluent R1. The governing equations and their respective boundary conditions were solved within a fixed-grid computational domain. The study focused on assessing the melting temperature of the phase change material (PCM), the spacing of heat fins, and the arrangement of the thermoelectric generator (TEG) to achieve the highest temperature difference in the TEG while reducing the surface temperature of the panel.

Transient heat transfer analysis was performed using a 3D geometry in ANSYS Fluent, with a time step set at 1 second and a total simulation time of 2 hours (7200 seconds). The simulation was initiated with the standard test condition (STC) of the PV panel, where the initial temperature was 25°C. The boundary conditions for the CFD analysis are illustrated in Figure 2. With the exception of the glass surface, all other outer surfaces were considered adiabatic, and the glass surface received 1000 W/m2 of solar radiation (as depicted in Figure 2). Consequently, the flow of the phase change material (PCM) was assumed to be laminar due to the absence of convective turbulence. The physical properties of the BIPV-TEG-PCM are detailed in Tables 1 and 2.

To optimize the system, the PiAnO software was employed to analyze the computational experimental data. The goal was to identify an optimal configuration where the PV panel generated the maximum daily electricity output while maintaining the thermoelectric element's temperature at its peak at both ends. For this purpose, a predictive model was developed to estimate daily power generation from the PV panel and the temperature at both ends of the thermoelectric element. This predictive model, combined with a weighting method, was then used to determine the optimal design parameters for the BIPV-TEG-PCM system.

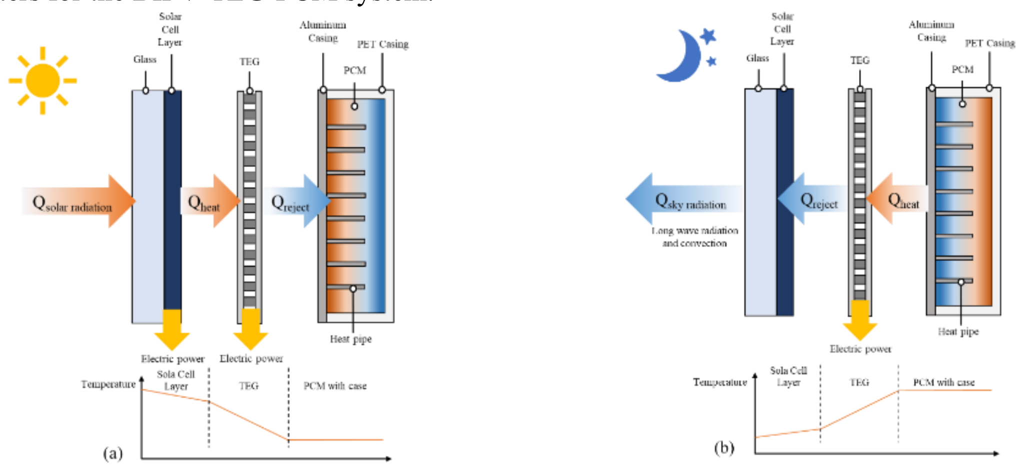

Figure 1. (a) BIPV-TEG-PCM operation during the daytime and (b) BIPV-TEG-PCM operation during the night

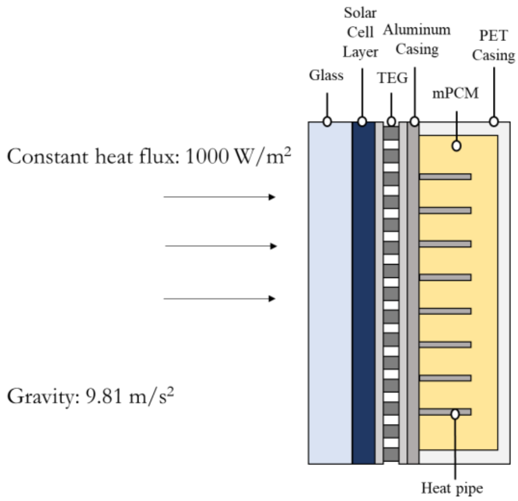

Figure 2. Geometry and boundary conditions for CFD

3. Simulation overview

In this study, the photovoltaic (PV) panel surface temperature of BIPV-TEG-PCM was simulated using finite volume discretization based on the computational fluid dynamics (CFD) ANSYS fluent R1. The solution for the governing equations and their specific boundary conditions is based on a fixed-grid computational domain. This study analyzed the melting temperature of phase change material (PCM), the heat fin spacing, and the thermoelectric generator (TEG) arrangement for the largest temperature difference in the TEG while lowering the panel surface temperature.

The transient heat transfer analysis was performed through ANSYS fluent with 3D geometry. The time step was set to 1 second, and the total simulation time was 2 hours and 7200 s. The simulation analysis was performed using the standard test condition (STC) of the PV panel as the initial condition (the initial temperature was 25°C). Therefore, the boundary conditions for CFD are shown in Fig. 2. Except for the glass surface, the rest of the outer surfaces were in adiabatic condition, and 1000 W/m^2 of solar radiation was received through the glass surface (Fig. 2). Therefore, in convective terms, turbulence does not occur in mPCM. Therefore, laminar flow is assumed to reflect the character of the mPCM. The used physical properties of the BIPVT-EG-PCM are shown in Tables 1 and 2 below.

In this study, the PiAnO software was used to analyze the computational experiment data for the optimization. The optimal point was aimed at deriving a point where the PV panel generates the largest amount of electricity per day and the temperature at both ends of the thermoelectric element can be maintained at the maximum. Therefore, the prediction function for the daily power generation amount of the PV panel and the temperature of both ends of the thermoelectric element was derived and used as the objective function. The optimal design point of BIPV-TEG-PCM was derived by applying the predictive model and weighting method.

Table 1. Properties of the mPCM for CFD simulation.

Description	Value
Melting temperature [°C]	25 - 60
Latent heat capacity [kJ/kg]	192.66
Specific heat capacity [kJ/kg]	1.97
Density [kg/m^3]	946.4
Thermal conductivity [W/mK]	0.749
Particle size [μm]	10

Table 2. Properties of the BIPV-TEG-PCM for CFD simulation.

Material	Density [kg/m^3]	Specific heat [J/kgK]	Thermal conductivity [W/mK]	Thickness [mm]
Glass	2200	830	0.76	3.2
PV	2230	700	148	0.5
EVA	960	2090	0.35	0.3
Aluminium	2719	871	202.4	3
TEG	7670	198	1.61	4
Heat fin	2719	871	202.4	3

4. Results and discussion

The OLHD (Optimal Latin Hypercube Design) was used to drive the computational experiment case for the meta model, which is a reinforcement model of the LHD method of a statistical tool called piano to derive a meta model. As the main factors, the interval of the thermoelectric element used in the parametric analysis, the temperature of the phase change material, and the interval of the heat fin were selected. Each variable was divided into 15 levels to derive a total of 15 cases. As the objective function, the daily power generation of the PV panel and the temperature difference of the thermoelectric element were selected.

In this study, the PiAnO software was used to analyze the computational experiment data for the optimization. As for the optimal point, the goal was to derive the point at which the temperature of both ends of the thermoelectric element could be maintained at the maximum while the daily power generation of the PV panel was the highest. Therefore, a prediction function for the daily power generation of the PV panel and the temperature at both ends of the TEG was derived and used as the objective function. At this time, a meta-model was derived with a Radial Basis Function (RBF) interpolation model suitable for computational experiments. The optimal design point of BIPV-TEG-PCM was derived by using the prediction model and applying the weight method.

5. Conclusion

This research employed numerical methods to assess the influence of heat fin spacing, TEG arrangement, and the phase change temperature on the BIPV-TEG-PCM system using transient CFD simulations. The integration of phase change material (PCM) was found to enhance the efficiency of photovoltaic (PV) panels, while simultaneously harnessing additional electricity generation through the Seebeck effect of the TEG. The simulations were conducted under standard test conditions (STC). The findings revealed that a lower phase change temperature effectively delayed the rise in PV panel temperature. Conversely, a higher melting temperature PCM, in conjunction with appropriate heat fin spacing, maintained similar temperatures over an extended duration. Thus, selecting the right melting temperature PCM, along with the correct heat fin spacing, can enhance PV panel efficiency. The optimization results indicated that, for the best performance of the PV cell and TEG in STC conditions, a PCM melting temperature of 40°C, a heat fin spacing of 12.4 mm, and a TEG distance of 187 mm were most effective.

Consequently, the BIPV-TEG-PCM system was demonstrated as a capable power generation system operating around the clock without additional devices. It achieved this by enhancing efficiency and utilizing waste heat sources, leading to the realization of zero-energy buildings. Recognizing the diversity of real-world environmental conditions, it is imperative to conduct regional optimization simulations that consider various environmental factors. Moreover, future research endeavors aim to create prototypes and assess their performance through field experiments.

Acknowledgments
This work was partly supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2022R1A4A1026503) and Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (20202020800030, Development of Smart Hybrid Envelope Systems for Zero Energy Buildings through Holistic Performance Test and Evaluation Methods and Fields Verifications).

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