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NUMERICAL INVESTIGATION OF ELECTRICITY GENERATION BY THERMOELECTRIC GENERATORS FROM PHOTOVOLTAIC PANELS COOLED BY PASSIVE COOLING METHOD USING HEAT PIPES

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ABSTRACT

The temperature of the photovoltaic modules is at the ambient temperature at sunrise, and the cell temperature increases during the day depending on the radiation intensity and the active cooling system. This increase in cell temperature causes a loss of efficiency in the PV panel. For this reason, PV panels are being tried to be cooled by different methods. This study covers creating a hybrid PV panel system that can generate electricity by the Seebeck effect of thermoelectric generators while cooling the overheated photovoltaic panel. With the hybrid structure created, both prevent the efficiency decrease caused by overheating in photovoltaic panels and electricity generation with a thermoelectric generator while cooling PV panels were examined. In the study, the average temperature of the PV/T panel system without a thermoelectric module was 45 °C, and the average temperature of the PV/T hybrid structure using thermoelectric was 47 °C. The thermoelectric generator's hot and cold surface temperatures were tested at 43 °C and 42 °C, respectively.

Keywords: Thermoelectric generator, Heat pipe, PV panel, Numerical analysis, Hybrid PV panel

1. INTRODUCTION

Environmental pollution has started to pose significant problems for humanity. Disasters such as droughts and floods experienced due to global warming have become frequent natural phenomena today [1]. However, environmental pollution also has serious adverse effects on the health of living beings [2]. Of course, the main factor of this environmental pollution is oil and its derivatives [3].

Today, due to industrialization, there is a significant increase in energy consumption. A large part of the energy consumed comprises fossil-derived fuels [4]. However, fossil fuels are the main factor in environmental pollution [5]. However, fossil fuels cannot meet today's energy needs, and it is estimated that these resources may be depleted soon due to their limited availability [6]. Therefore, due to these energy-based problems experienced today, there has been a rapid orientation to renewable energy sources, also called clean Energy [7]. Renewable energy sources are environmentally friendly but have unlimited resources. The most significant increase in renewable energy sources in the coming years may be experienced in solar energy [8].

Electricity can be generated directly from solar energy through photovoltaic panels. However, the efficiency of these devices is around 20%, and this rate is considered very low [9]. For this reason, much research is being done on photovoltaic panels. In this study, it was investigated numerically to prevent the efficiency decrease caused by overheating in photovoltaic panels and the ability to generate electricity with a thermoelectric generator while the photovoltaic panels are cooled.

1.1.Thermoelectric Modules

Thermoelectric modules are manufactured from N- and P-type semiconducting substances obtained by adding certain atoms to thermoelectric semiconducting substances. In N-type semiconductors, thermal energy is carried by free electrons in the material, while in P-type semiconductors, it is carried by cavities. A thermos-element is a single P- and N-type semiconductor substance that works with this principle. The thermoelectric effect is formed by connecting N and P-type semiconductor thermos-elements in series with conductors. To add strength to the thermoelectric module, ceramic layers known to have a high heat conduction coefficient and low electrical conductivity are added to both sides of the thermoelectric module. The cross-sectional view of the thermoelectric module is shown in Figure 1 below it is shown in [10].

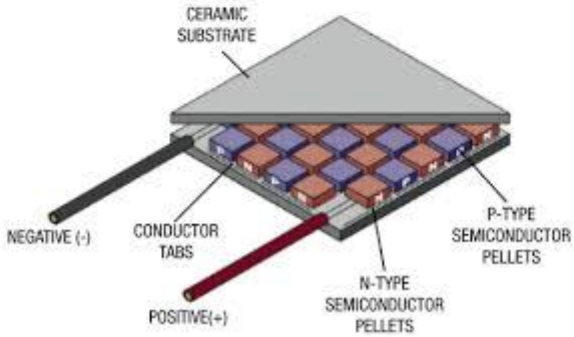

Fig. 1. Cross-sectional views of the thermoelectric module [10].

Thermoelectric modules can be used reversibly as thermoelectric generators (TEG) and coolers (TEC). For this reason, it is necessary to produce the thermoelectric module suitably for the intended use. TEG and TEC modules can be used interchangeably, but the desired effect cannot be demonstrated. The processes occurring from the thermoelectric module are examined in three ways Seebeck, Peltier, and Thomson effects [11].

The Seebeck effect; In an experiment by Thomas Seebeck, two pieces of wire made of different metals were joined at their ends, and a temperature difference was applied to the joined ends. Although no electric current is passed through the installed circuit, a potential difference (ΔV) occurs from the voltmeter connected to the circuit. This is called the Seebeck effect, and this circuit created is called a thermocouple [12].

The Peltier effect: In the Seebeck effect, it has been observed that when two wire parts are joined at the ends and heated, a voltage is formed on the wires. Under the Peltier effect, an electric current was passed through the wires, and because of the test, it was observed that the temperature of one of these wires decreased while the temperature of the other wire increased. This is called the Peltier effect [13].

The Thomson effect is when different temperatures are applied at the two ends of a conducting material. Energy is absorbed or accumulated through the conducting material depending on the current direction [14].

1.2. Photovoltaic Panels

Photovoltaic panels form the basis of the systems developed to obtain direct electrical energy from solar energy [15]. The efficiency of photovoltaic panels depends on the module material composition, radiation intensity, ambient temperature, and module temperature [16]. The air temperature is relatively high in many regions of the world, especially in certain parts of time, which harms photovoltaic panels. The temperature of the photovoltaic modules is at the ambient temperature at sunrise, and the cell temperature increases during the day depending on the radiation intensity and the active cooling system. The surfaces of the solar cells in black or close to black colours form ideal layers for heat absorption [17]. An experimental study observed that the photovoltaic surface temperature rose to a temperature of 80°C in about 50 minutes. This increase in surface temperature reduced the efficiency of photovoltaic panels from 11.9% to 8% [18].

Efficiency losses are experienced due to the overheating experienced in photovoltaic panels. Therefore, cooling methods such as heat pipes, phase-changing material (PCM), finned heat sinks, thermoelectric modules, evaporation, micro-cooling fluid channels, and coolant spraying are applied for cooling photovoltaic panels [19]. This study reduces the instantaneous temperature changes of photovoltaic panels and the average temperature values. Additionally, it has been tested whether the heat difference obtained while cooling the photovoltaic panels is sufficient for electricity generation from thermoelectric generators. For this purpose, the temperatures of the hot and cold surfaces of the thermoelectric generator were estimated in this study.

2. MATERIAL AND METHOD

In this study, it was investigated whether the temperature difference that will occur during the cooling of the overheated photovoltaic panels with the passive cooling system formed by heat pipes and heat sink aluminium flat sheets has the potential to generate electricity with thermoelectric generators. The thermoelectric generators used in the study are designed to consist of ceramic, N and P-type semiconductor layers and conductive material as shown in Figure 1. For this purpose, a hybrid panel was created by placing the hot side of the thermoelectric generator in contact with the back surface of the photovoltaic panel and the cold side of the thermoelectric generator with the heat pipe. This hybrid structure will be pronounced as PV/T-TEG in the continuation of the study. The formation of the temperature difference at which electricity can be produced from this hybrid structure according to the Seebeck effect principle of thermoelectric generators has been numerically investigated.

In the study, aluminium heat sinks with circular fins were added to the condenser parts of the heat pipes. Thus, it is aimed to accelerate the transition of heat in the condenser to ambient air. To facilitate the transfer of heat from the PV Panels to the heat pipes, flat aluminium sheets and the evaporator parts of the heat pipes were brought into contact with each other. The condenser parts of the heat pipes are designed to be above the top level of the panel, as shown in Figure 4.5. It was thought that the condenser parts of the heat pipes were insulated with a shading system that would prevent them from being affected by the sun but would not interfere with the natural airflow.

The numerical analysis study tried estimating the surface temperatures of PV/T-TEG and conventional PV panels through the ANSYS program. In the study, first, the heat pipe was modelled with the design modeller program regarding the flow chart shown in Figure 2, and numerical analysis was performed with the fluent program.

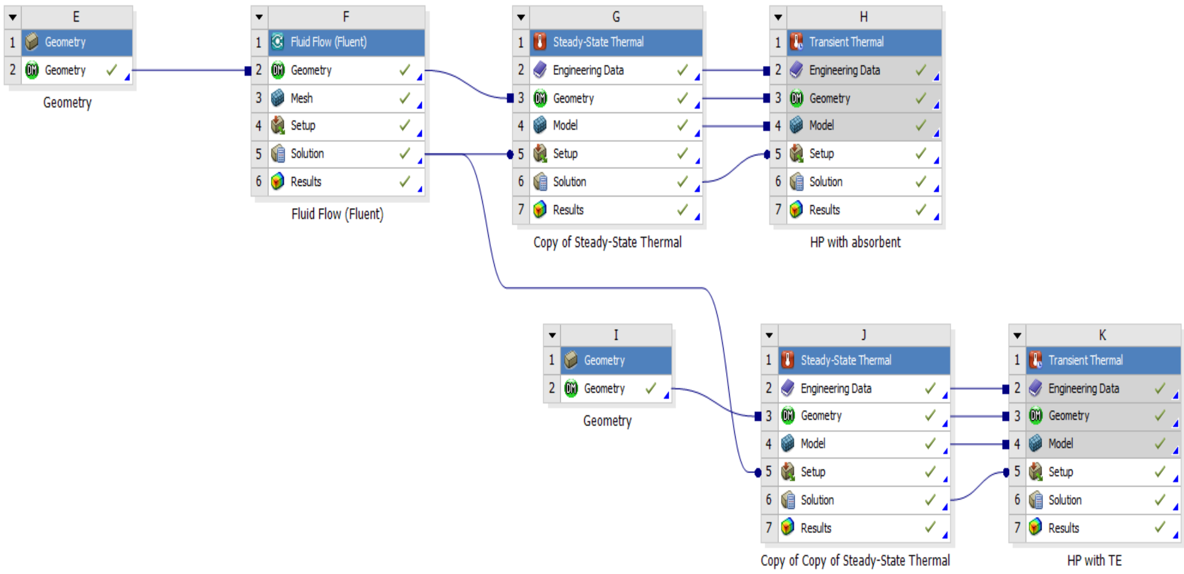

Fig. 2. Design and analysis flow diagram of the heat pipe

The photovoltaic panel, whose numerical analysis was performed, consists of glass, EVA, photovoltaic cell, EVA and Tedlar layers [20]. According to these components, the parts whose design and analysis were completed were combined with the design model program to suit the PV/T panels in the experimental study. In the study, the design and analysis of the reference PV panel were carried out using the flow chart shown in Figure 3. The surface temperature analyses of the PV/T-TEG and reference panels were carried out with a steady-state thermal program. The working conditions were radiation 900 W/m2, ambient temperature 34 °C and heat transfer with convection 15 W/m2. The material dimensions used have been determined as optimum for the system to be easily analysed in a computer environment.

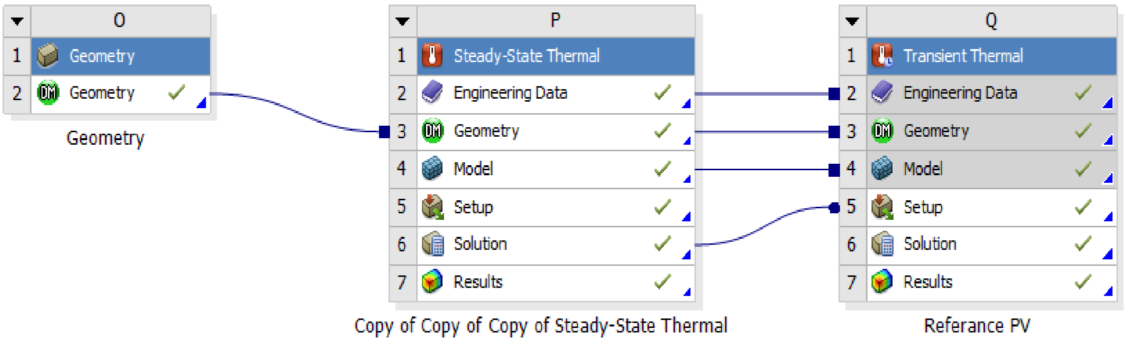

Fig. 3. Design and analysis flow chart of the reference PV panel

2.1.Thermophysical Properties of The Materials Used in The Study

In the study, numerical analysis was carried out considering the characteristics of the monocrystalline panel. In order for the system to be easily analysed in the computer environment, the material dimensions used were determined as optimum. This study is not for electricity generation, but it was conducted to determine whether the potential temperature difference in the system has the ability to produce electricity with thermoelectric generators. In this context, since the technical features of photovoltaic panels are not needed in the study, only the thermophysical properties of the components of photovoltaic panels are given in Table 1.

Table 1. Technical characteristics of the photovoltaic panel [20].

Component	Parameter	Symbol	Value	Unit
PV/T Collector	Collector area	A	0.012	m2
	Collector Tilt	o	30	
	Length	$l_{pv/th}$	0.12	m
	Width	w	0.1	m
	Thickness	$\delta_{pv/th}$	0.006	m
Tampered Glass	Specific Heat Capacity	C_{p_g}	677	J/kgK
	Density	ρ_g	3000	kg/m3
	Emissivity	ε_g	0.92	
	Absorptivity	α_g	0.05	
	Conductivity	k_g	1.8	W/mK
	Thickness	δ_g	0.0035	m

PV Cell	Specific Heat Capacity	$C_{p_{pv}}$	677	J/kgK
	Density	ρ_{pv}	2330	kg/m3
	Emissivity	ε_{pv}	0.88	
	Absorptivity	α_{pv}	0.95	
	Conductivity	k_{pv}	148	W/mK
	Thickness	δ_{pv}	0.0025	m
	Transmissivity	τ_{pv}	0.88	

A heat pipe made of copper material was used in the study. Since the heat pipes will work based on gravity, wicks were not used in these heat pipes. Acetone was used as the working fluid in the heat pipes. The general characteristics of the heat pipes used are given in Table 2.

Table 2. Characteristics of heat pipes [20].

Component	Parameter	Symbol	Value	Unit
Heat Pipe (Copper)	The outer diameter of the evaporator section	$d_{o,eva}$	12	mm
	The inner diameter of the evaporator section	$d_{i,eva}$	10	mm
	The outer diameter of the condenser section	$d_{o,con}$	12	mm
	The inner diameter of the condenser section	$d_{i,con}$	10	mm
	Conductivity	k_{hp}	394	W/mK
	Length of the evaporator section	l_{eva}	120	mm
	Length of the condenser section	l_{con}	50	mm
	Wall thickness of heat pipe	δ_{hp}	1	mm
	Density	ρ_{hp}	8933	kg/m³
	Specific heat capacity	$C_{p_{hp}}$	385	J/kgK

In the study, circular fin heat sinks, flat fins and heat sink flat plates were used as aluminium material. The characteristic properties of these materials are given in Table 3.

Table 3. Characteristics of aluminium materials [20].

Component	Parameter	Symbol	Value	Unit
Aluminum Fin/Sink/Plate	Specific Heat Capacity	$C_{p_{al}}$	903	J/kgK
	Density	ρ_{al}	2.699	kg/m3
	Emissivity	ε_{al}	0.55 - 0.75	
	Conductivity	k_{al}	205	W/mK
	Thickness	δ_{fin}	1.5	mm
	The outer diameter of the aluminium heat sink	$d_{o,sink}$	40	mm
	The inner diameter of the aluminium heat sink	$d_{i,sink}$	12	mm
	Length of the aluminium heat sink	l_{sink}	15	mm
	The thickness of the aluminium plate	δ_{plate}	0.02	mm

3. RESULTS AND DISCUSSION

3.1.Reference photovoltaic panel

At this stage, the reference photovoltaic panel was designed with the help of ANYSY-Design-modeller and tried estimating the photovoltaic panel cell temperature by analysing it through Fluent software. As can be seen in Figure 4, because of the analysis, the reference photovoltaic panel cell temperature was realized as an average of 55 °C.

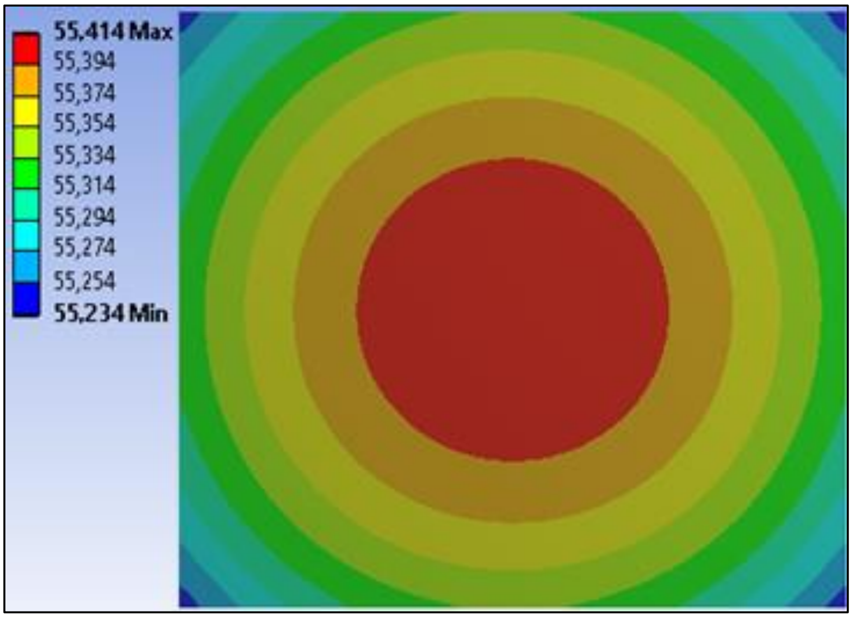

Fig. 4. Surface temperature distribution of the reference photovoltaic panel

3.2. Passive Cooling System (PV/T-P)

A flat aluminium sheet with a thickness of 0.2 mm has been integrated into the traditional PV panel to increase heat absorption from the heat pipes and panel, as shown in Figure 5. Additionally, a circular aluminium heat sink has been added to the condenser part of the heat pipes to accelerate heat excretion into the ambient air. This PV panel system created will be pronounced as PV/T-P in the continuation of the study. The analysis was carried out without adding thermoelectric generator modules to the PV/T panel system created at this stage. Because of the analysis, the average temperature of the photovoltaic panel (PV/T-P) was determined as 45 °C. The result of the study is given in Figure 6.

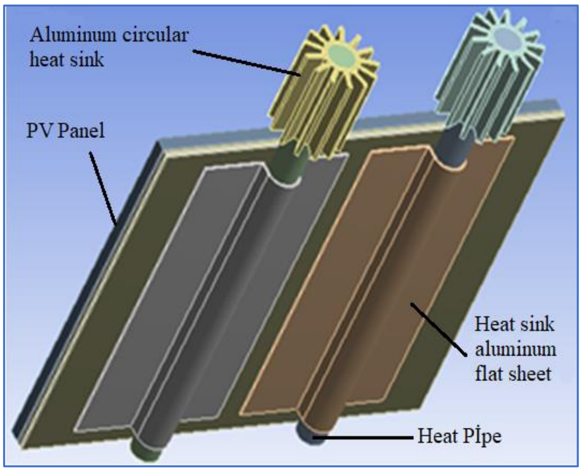

Fig. 5. PV/T-P panel appearance

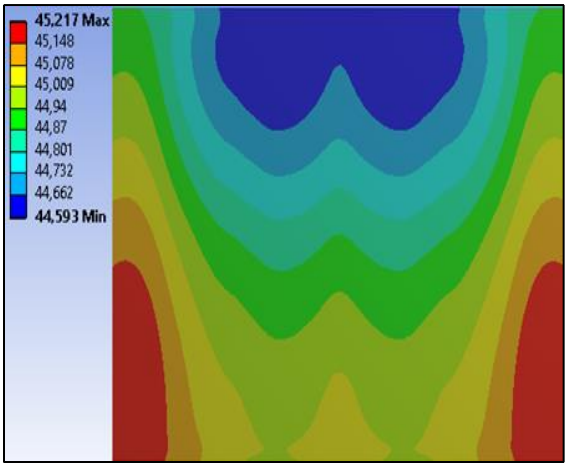

Fig. 6. Surface temperature distribution of PV/T-P panel

Fig. 4 and Fig. 6 Compared, it is seen that the temperature of the conventional photovoltaic panel was reduced by about 10 °C as a result of cooling with the PV/T-P passive cooling system.

3.3. Hybrid Panel System (PV/T-TEG)

At this study stage, thermoelectric generators were added to the system designed as PV/T-P, as shown in Figure 7. In this context, a hybrid photovoltaic panel (PV/T-TEG) system was created by contacting the hot side of the thermoelectric module with the back surface of the photovoltaic panel and the cold side of the thermoelectric module with heat pipes and flat aluminium plate. It was attempted to determine by numerical analysis whether the heat difference resulting from this hybrid photovoltaic panel system obtained is sufficient for the thermoelectric generator to generate electricity.

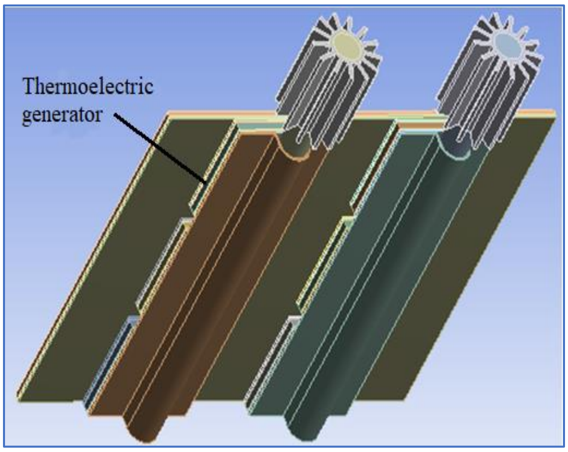

Fig. 7. PV/T-TEG panel appearance

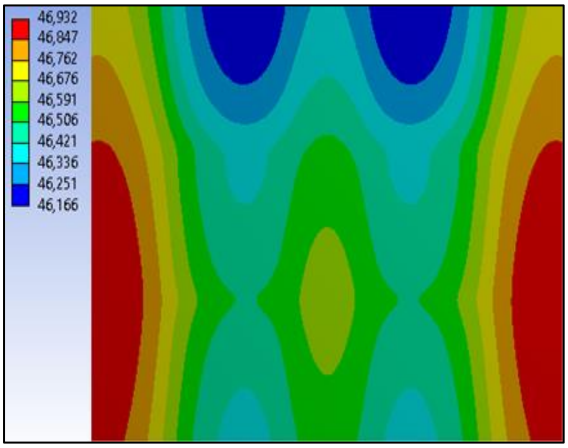

Fig. 8. Surface temperature distribution of PV/T-TEG pane

The values obtained because of the analysis performed are shown in Figure 8. The average temperature value of the PV/T-TEG panel system was approximately 47 °C. The system using a thermoelectric module and the system not using a thermoelectric module are given in comparison in Figure 9.

According to this result, it has been determined that the thermoelectric modules create thermal resistance between the photovoltaic panel and the heat pipe, Therefore the hybrid panel was cooled about 2 °C less than the PV/T-P panel without the thermoelectric module.

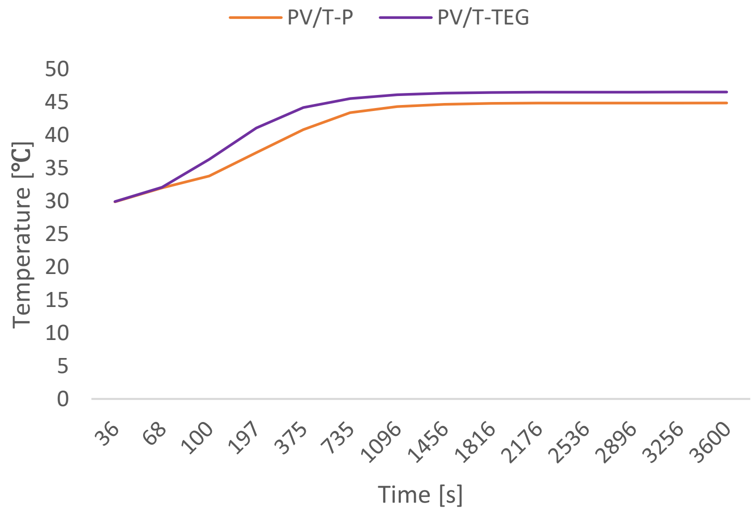

Fig. 9. Comparison of PV/T-P system and PV/T-TEG hybrid system

Additionally, the temperature values of the hot and cold surfaces of the thermoelectric generator were measured in the study and Figure 10. And Figure 11. It is shown in. According to the results obtained, the average hot surface temperature of the thermoelectric generator was 43 °C and the average cold surface temperature was 42 °C.

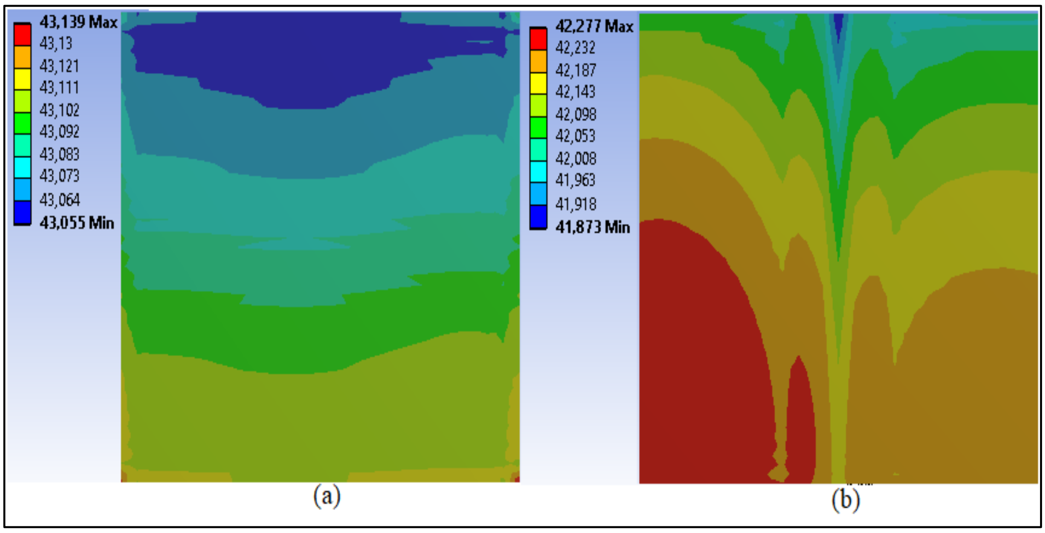

Fig. 10. Temperature distribution of Thermoelectric Module (a) Hot surface, (b) Cold surface

It is seen that the temperature difference between the hot and cold surfaces of the thermoelectric generators (TEG) is about 1 °C as seen in Figure 12. The effectiveness of passive cooling methods directly depends on ambient conditions (ambient temperature, wind speed). With passive cooling methods, the cooling process can take place more slowly than with active cooling methods. Although the PV panel temperature was reduced by 10 °C with the PV/T-P passive cooling method tested in this study, this cooling process was insufficient to create the desired temperature difference between the surfaces of the thermoelectric generator.

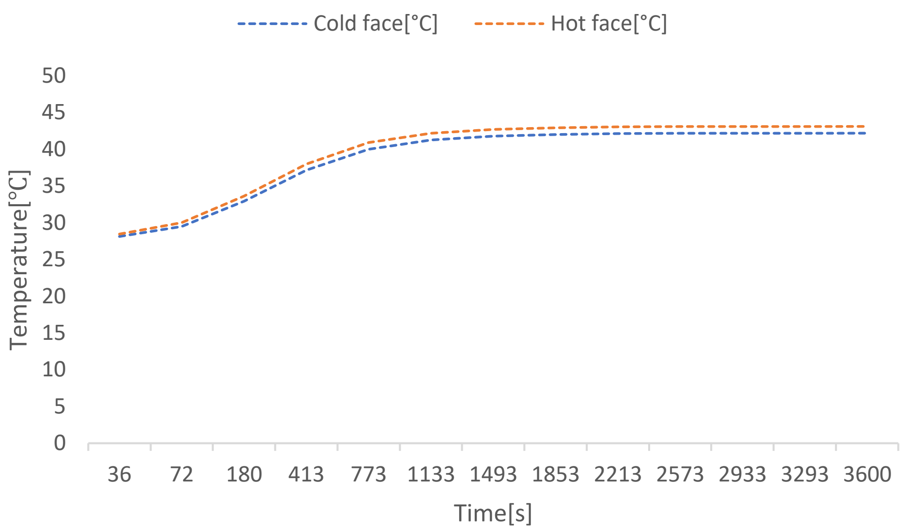

Fig. 12. The temperature difference between the surfaces of the thermoelectric generator

In the literature research conducted, it has been stated that there should be at least a 20 °C-temperature difference to generate electricity with thermoelectric generators. The electrical energy values that can be generated from the thermoelectric module according to the temperature differences are given in Table 4 [21,22].

Table 4. The electrical power generated by the thermoelectric generator according to the temperature difference [21].

Temperature Difference	Open-Circuit Voltage	Current
20 °C	0.97V	225mA
40 °C	1.8V	368mA
60 °C	2.4V	469mA
80 °C	3.6V	558mA
100 °C	4.8V	669mA

The findings from the numerical study and the information obtained from literature research reveal that the efficiency of thermoelectric generators will be low in hybrid systems with passive cooling, such as PV/T-TEG. Additionally, this study reveals that the PV/T-TEG hybrid system will have a lower cooling efficiency than the PV/T-P panel system because its cost will be high.

4. CONCLUSIONS

This study covers creating a hybrid structure by placing thermoelectric generators between the back surface of the heated photovoltaic panel and the heat pipe cooling system used for cooling the PV panel. With the hybrid structure created, both the prevention of the decrease in efficiency due to overheating in the photovoltaic panels and the ability to produce electricity with the thermoelectric generator. In contrast, the PV panels are cooled and investigated numerically.

This study was conducted at an ambient temperature of 34 °C, and the average surface temperature of the reference PV panel was 55 °C under these conditions. However, in actual conditions, the surface temperature of the PV panel can increase up to 80 °C depending on parameters such as the ambient temperature, wind speed and solar radiation speed [14]. Therefore, depending on the PV panel temperature, there will also be an increase in the temperature difference between the surfaces of the thermoelectric generator. In an experimental study with passive cooling, they determined that the temperature difference between the surfaces of the thermoelectric generator was 26 °C when the PV panel temperature reached 80 °C.

However, looking at the values in Table 1, it can be said that this temperature difference is too low to generate electricity with thermoelectric generators. In the same study, when forced cooling was preferred instead of passive cooling, the temperature difference between the surfaces of the thermoelectric generators was 51 °C [23]. This value obtained is approximately twice the value obtained with passive cooling.

The findings obtained in this study and literature research revealed that more than the temperature difference to be obtained from PV/T panels cooled by passive cooling methods would be required for electricity generation with thermoelectric generators. Additionally, this study has also shown that thermoelectric modules can create thermal resistance between the PV panels and the cooling apparatus, causing the system's cooling efficiency to decrease.

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