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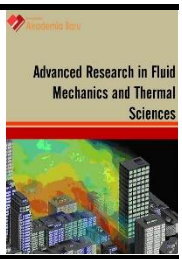

Computational Fluid Dynamics Analysis of Thermoelectric Generators Performance under Solar Photovoltaic-Thermal (PVT) System

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ABSTRACT

Solar radiation could be harnessed to produce thermal and electrical energy. The solar thermal radiation is very advantageous as it can be harnessed easily and at an affordable cost. Electrical energy could be produced from the solar radiation by photovoltaic process and have an efficiency of 20-40%. This process is currently limited to its material and manufacturing costs, inefficiency under thermal load and relatively lower performance under low clearness index conditions. By using both properties, a solar photovoltaic-thermal (PV/T) hybrid could be designed to increase thermal and electrical efficiency during low clearness index. The study of the potential application of Thermoelectric Generator (TEG) in PV/T applications is highlighted to see the opportunities that are available in this field of study. Computational Fluid Dynamics (CFD) simulation using COMSOL software was carried out.

1. Introduction

The pursuit for clean and sustainable energy had increased over the years as the depletion of fossil fuel sources and demand in energy keeps getting larger by the year. This factor plays a crucial role in determining the price of fossil fuel. Therefore, it is only logical to find an alternative source which is reliable, sustainable and are not affected by political climate. Solar, wind, hydro, tidal waves, biomass and geothermal heat are among the sources that are readily available and geographically specific. With specific technology applications, the renewable energy sources can help reduce the

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dependency to fossil fuel, cut down the carbon emission and provide a sustainable environment for future generations [1-7].

Solar radiation is the most abundant renewable energy source on this planet with 105 TW solar rays coming in contact with the earth's surface. This source actually drives other energy sources creating wind, ocean tide and thermals, fossil fuels, biomass and biogas, hydro and photosynthesis. The direct resource could also be harnessed into thermal and electrical energy. Therefore, it should not to be taken lightly the contribution of solar to our energy resources. The next step is to harness the solar energy directly by form of light spectrum. This spectrum can produce two energies, thermal and electricity. Thermal energy is produced by means of thermal radiation from the sun absorbed by a body while electricity is produced as a result of a thermal difference or reaction of electrons due to photons travelling to a material and exciting the electrons in it. The past 50 years has seen a steady advancement in solar renewable energy studies while also gaining interests among the publics for its applications [8-16]. With this in mind, a future where continuous viable and cheap renewable energy resource is not too far away.

Solar radiation could be harnessed directly by the form of light spectrum. This spectrum travels in a form of photons with different wavelengths. It consists of UV light, visible light and Infra-red. Thermal energy is produced by means of thermal radiation from the sun absorbed by a body while electricity is produced as a result of a certain amount of bandgap existing in the metal or ceramic materials and only utilize the visible light.

Extraterrestrial solar radiation will travel into the earth's atmosphere at a certain constant. To arrive on a module, the radiation will be filtered by various weather factors and pollution, while dependent of the earth's orbital position, the module's location and its position towards the sun. These factors will determine the amount of solar irradiation that arrives onto the module. Figure 1 shows the methods that can be used to harness energy from solar radiation.

The past 50 years has seen a steady advancement in solar renewable energy studies while also gaining interests among the publics for its applications. With this in mind, a future where continuous viable and cheap renewable energy resource is not too far away.

Solar energy currently employs two methods in harnessing the solar radiation, thermal energy and electrical energy [17-18]. Thermal energy has been discovered since the early human civilizations for drying foods, clothes, creating drafts, etc. Today, the applications had advanced into cooking, mass drying, building heating and cooling, food cooking and processing, hot water supply etc. Some of the most advanced type of solar thermal technology is using an array of heliostats focused on a tower to heat salt until it is molten and used the heat stored to produce superheated steams and run a steam turbine. Another form of method is by using the change in electrical charges in a solid state material to move electrons through materials. This is used in the physics of solar photovoltaic to create electrical energy. This form of physics uses fewer amounts of materials and mechanical parts than a thermal energy application [19]. It is a relatively new form of knowledge and its full potential has only been fully discovered in the 70's. The only backside of it is its lower efficiency and will continue to reduce under thermal stresses compared to a thermal application [20-23]. To avoid this problem, a new method is needed to maintain the efficiency of a photovoltaic system while harnessing the solar thermal energy. Therefore, this paper will analyze the potential application of thermoelectric generators and their performances in solar PV/T applications.

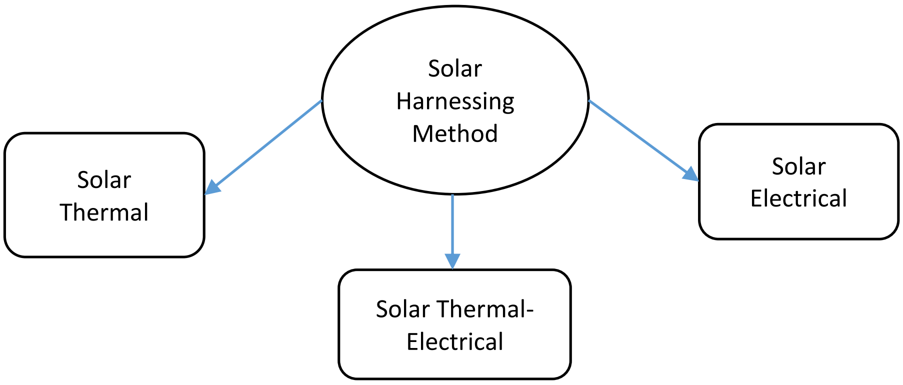

Fig. 1. Solar harnessing method

2. Methodology

2.1 Thermoelectric Generators Working Principles

A thermoelectric generator (TEG) takes the advantage of having two dissimilar metals having temperature difference at its joints resulting in a flow of current perpetuated by an electromotive force existing in the circuit established by the two joints [24]. Negative charge electrons in the n-leg and positive charge holes in the p-leg will move from the side with the heat source to a colder side creating temperature gradient. Hence, this produces the current flow. The amount of voltage difference increases as more temperature difference available. This is called the Seebeck effect founded in 1821 by Thomas Johann Seebeck. It has a constant, S, proportional to its voltage and temperature difference and it is expressed in V/K.

$$\Delta T = \frac{-\Delta V}{S} \tag{1}$$

However, there will be no electromotive force in the thermoelectric module if the p and n leg have similar material even if their Seebeck constant is high. Metals usually have smaller Seebeck constant compared to semiconductor materials which is why more of semiconductor materials are being applied in this application.

A thermoelectric could also be used for heating by connecting to an electrical supply. The current flow will determine the side which will reject or absorb the heat in the TE. This is then called the Peltier effect. This effect was discovered in 1834 by Jean Charles Athanase Peltier. It also uses the same layout as a Seebeck TE where two joints of dissimilar material excited by current. The Peltier performance can be determined by a dimensionless parameter, ZT, when heat is absorbed in the area of the joint per second [25].

$$ZT = \frac{S^2}{k}\sigma T \tag{2}$$

In Eq. (2), σ represents electrical conductivity, k as thermal conductivity and T as absolute temperature. A TE thermocouple can be arrange into a TE module that will consists of arrays of p and n legs electrically connected in series but stacked thermally in parallel [26-27]. This module is capable of operating with both Seebeck and Peltier effects. To measure the efficiency of the TEG, temperature at the hot and cold side is needed and known Seebeck coefficient of the material used [28].

$$\eta_{eff} = \frac{T_1 - T_2}{T_1} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_2}{T_1}} \quad (3)$$

where T1 is the temperature for the hot side and T2 is the temperature for cold side. This equation describes the Peltier and Seebeck. The Seebeck effect creates electrical current in the solid state material when temperature difference between the material surfaces is available. Meanwhile, the Peltier effect uses the energy supplied flowing through the thermoelectric material and results in an energy consumption and turning one side of the material hotter.

2.2 Materials Configurations

Based on current researches, it can be concluded that there are multiple configurations that can be used in a PVT-TEG module and can be tabulated as in Table 1.

Table 1
Configurations available for a PV/T hybrid assembly that can also be applied to thermoelectric generator configuration [29-38]

Types of Components					
PV Cell	Concentrator	Heat Exchanger	Absorber	Fluid Medium	Glazings
Monocrystalline	Fresnel	Heat sink	Selective surface	Air	Non-reflective glass
Polycrystalline	Flat Reflectors	Heat Pipes	Spectrum filter	Water	Vacuum tube
Amorphous	Parabolic	Microchannel	Flat plate	Oil	
Multi-Junction	Through	Finned		Nanofluid	
Thermo- photovoltaic	Optical lenses	Corrugated		Methanol	
		Channeled			

Based on the hybrid systems that had been studied before, there were two main areas that were directly affecting the TEG module, the absorber and heat exchanger. The absorber functions as the main heat collector that will distribute the heat evenly before transferring to TEG via conduction or convection processes. This will be connected to the TEG on its hot side. The design will determine how effective solar radiation will be absorbed without having too much heat loss. Some studies would also ignore using and absorber and directly connects with a TEG surface.

The heat exchanger meanwhile will function as a mechanism that will have a continuous heat flux from the TEG to the environment, thus providing efficient cooling on its cold side [39-40]. The optimization of these two areas will increase the effectiveness of the TEG side of the hybrid system by increasing the temperature difference. This is important as ZT is linearly dependent of ΔT.

3. Simulation Study

Figure 2 shows the 2-D Simulation setup of a TEG on PV/T application using COMSOL. The study of TEGs under the application of solar PV/T would indicate to get a sense of thermal energy removed from an average solar cell, through the temperature of PV panel and increasing the PV panel's efficiency, at the same time, the amount of electricity generated from the waste heats. The PV panel temperature would start at 345.15K, a typical temperature accumulated under 800-1000W/m^2 solar irradiance [41-43]. The ambient temperature will be at 303.5K. A single channel single pass air-based solar collector will be constructed underneath the PV panel as a means of heat extractor and providing the temperature difference needed by the TEG to start generating electricity. The size of the collector will be 1.6m by 1m, the size of a 120W PV panel. The inlet and outlet design of the air collector was to be in diverging-diverging configuration. The side and back walls were assumed to be well-insulated with no loss of energy.

The inlet speed of the solar collector was 0.01m/s and outlet speed at 0.4m/s assuming that a forced flow was created at the end of the collector to remove heat from the system. Heat will only be transferred through the TEGs as insulation was assumed to be present under the panel except around the TEGs. Heat loss was also assumed to be negligible behind the panel.

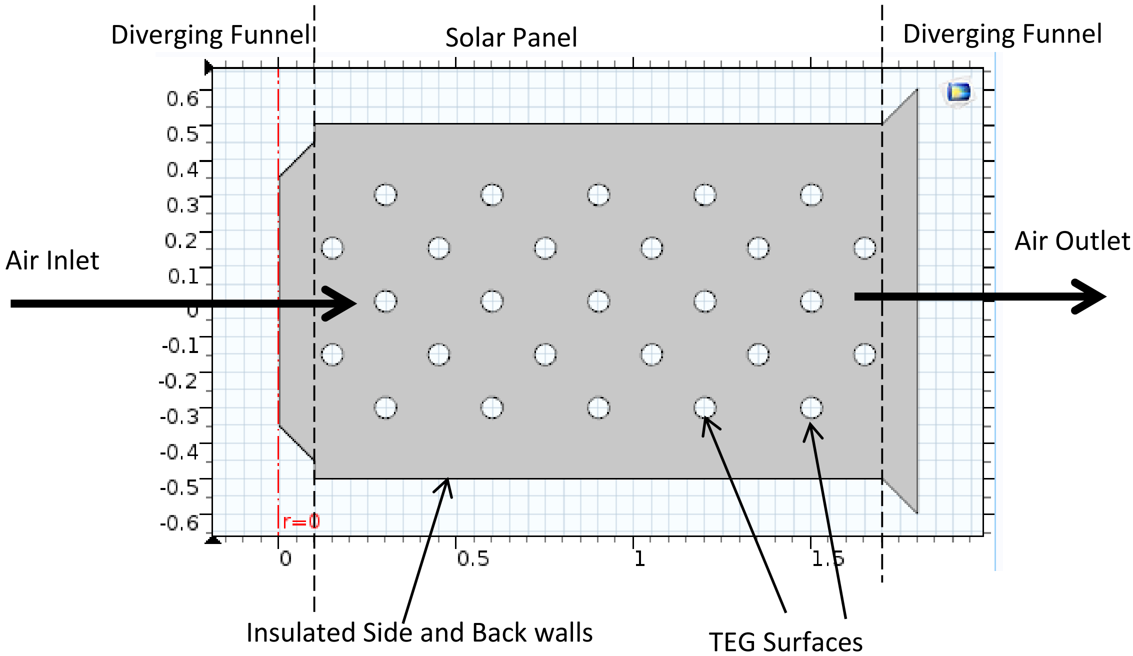

Fig. 2. 2-D Simulation setup of a TEG on PV/T application using COMSOL

27 TEGs represented in by a circular shape and assemble in a half dropped fashion. The TEG's have a diameter of 0.04m each. This results in a total of 0.035m^2 of the total surface area of the PV panel. The air flow rate will be simulated at 1 m/s. The air movement and amount of temperature difference that will be achievable in this setup was investigated. This was necessary to predict the amount of power that can be generated by the TEGs and also efficiency gained from the drop in cell temperature.

Figure 3 shows the mesh sizes and it will be set to automated normal distribution and controlled by the physics of the simulation. A time-dependent study was made to see the heat flux removed from a stagnant solar collector panel with the presence of TEGs. This will also determine the movement of air and to identify any areas that were not affected by the air flow.

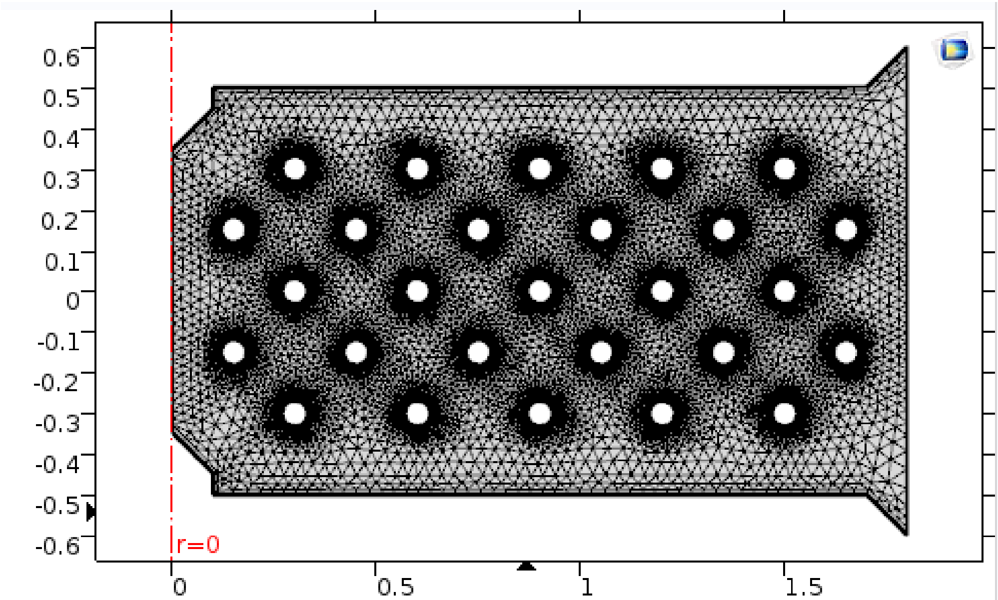

Fig. 3. Physics generated Mesh generated by COMSOL which will demonstrate the heat flux

4. Results

The result from this simulation showed the distribution of temperature inside the single channel single pass air based solar collector. Figure 4(a)-(f) showed the temperature distributions at 0, 4, 8, 12, 16 and 30s. The initial temperature started at 345.15K for the entirety of the system to simulate the condition of stagnant air under the solar collector. As the outlet flow started to increase to 0.4 m/s, we could see the temperature started to decrease to ambient at the inlet.

As the air moved around the TEGs, air temperature increased, removing the heat from TEG. The TEG created small vortices shape upon the temperature distribution as the air flow started to increase around the TEG. Small trails of higher temperature could still be seen at the 16th second where heat was still being removed. Finally, at the end of the simulation, at the 30th second, all the temperatures had arrived to a steady state. It was observed there was still a small portion of the area that was not affected by the heat removal process located to the side of the solar collector. This was due to the boundary layer created by the friction between the air and material of the side collector. It was also affected by the previous assumption that there was no heat loss at the side walls.

The highest temperature difference achievable at the end of the simulation was 41.65K. This temperature was distributed evenly on the surface of the solar collector. The TEG could generate electricity by using this temperature difference. The highest possible efficiency of the TEG was 4.65%. From the observed results, it can be concluded that the TEG surfaces may also act as an extended surface with moderate performance.

The use of TEG effected the efficiency of PV panel resulted in 9.1% overall efficiency increment. The TEG efficiency can be added to the PV panel's efficiency with cell temperatures at a lowered value resulting in higher total electrical efficiency. The maximum air speed achievable in this simulation was 0.745m/s as it approached at the end of the diverging nozzle, at each corner and in between the TEGs. This speed dropped back to its outlet speed of 0.4m/s shown in Figure 5.

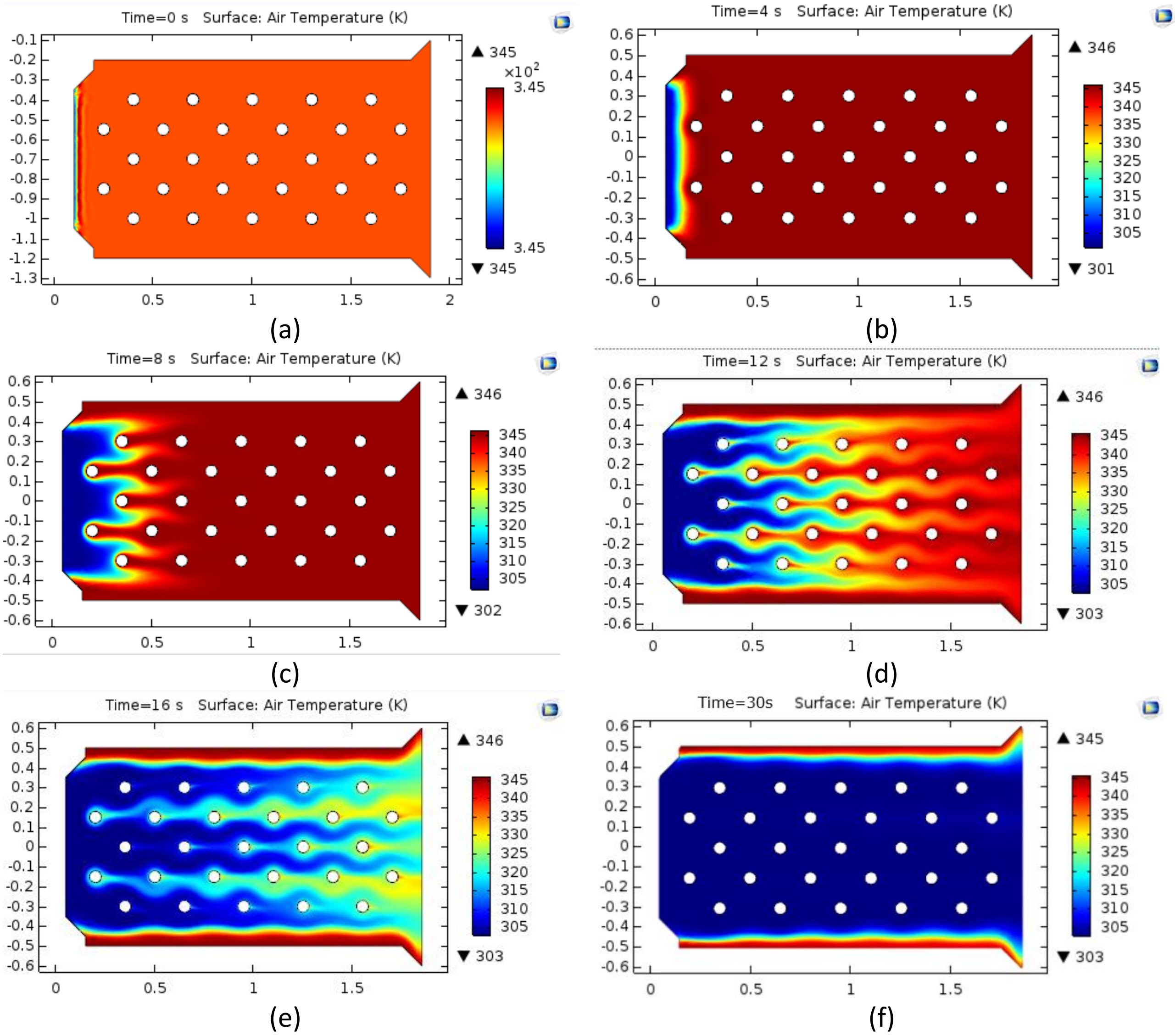

Fig. 4. (a)-(f) Simulation demonstrating the surface temperature distribution using time-dependent analysis

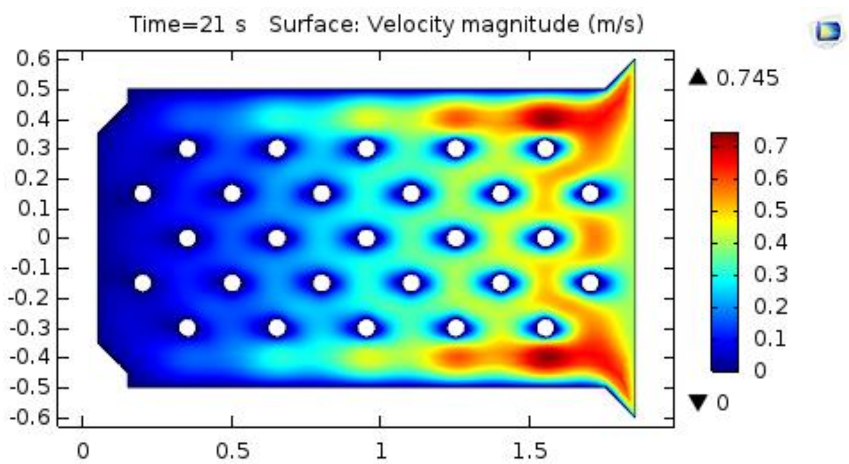

Fig. 5. Simulation demonstrating the surface temperature distribution using time-dependent analysis

5. Conclusions

A CFD analysis was carried out to investigate the performances of TEGs under solar PV/T system. 27 TEGs were located normal to the non-generating surface of a PV panel and a forced air flows on the surface of the panel through two diverging ducts at the inlet and outlet of the PV/T system. This simulation showed the potential application of TEG in PV/T applications.

i. It was possible to generate more electricity, 4.65% efficiency achieved by TEGs
ii. Cool down the temperature of solar PV panel from 345.15K down to 305.7K at most of the area.
iii. Resulted in a higher overall efficiency system, 9.1% increment by the PV.
iv. TEG was also seen as a good thermal conductor, acting as an extended surface.

In future studies, thermal conduction in the PV/T–TEG sandwich will be simulated with more information using the thermal properties of each material. The energy balance equation will also be implemented to derive the efficiency of the system. This will further improve on the simulation and provide a better result on the system's efficiency.

Applications in the solar thermal energy field are promising as the potential to harness the balance energy from the back of a solar panel is significant. It also increases the efficiency of the solar panel as it acts as a type of extended surface.

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