THERMOELECTRIC GENERATOR (TEGs) AND HEAT RECOVERY

TERM PROJECT

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ABSTRACT

This research discusses thermoelectric generators and heat recovery. The aim of this report is to clarify how thermoelectric generator works and review some heat recovery methods. First the report lights the fundamentals of thermoelectric generators including the main concept, the Seebeck effect, and the Peltier effect. Then, the report discusses the advantages of using thermoelectric generators for heat recovery in many other systems, and heat recovery methods including the heat exchanger and phase change materials. The report concludes that the thermoelectric effect is a way to create a thermoelectric generator, which in turn is a way to recover lost heat in other systems.

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LIST OF SYMBOLS AND/OR ABBREVIATIONS

TEGs	Thermoelectric generators
HX	Heat exchanger
PCMs	Phase change materials

INTRODUCTION

Thermoelectric technology was revealed during the World War II by the Soviet scientist Abram Ioffe, when he produced a 4-watt thermoelectric generator capable of powering a small radio through slight cooking fire, by simple device we can convert heat directly to electricity. The basic principle that used on this device for its operation was discovered by the physicist Thomas Johann Seebeck, in 1822 he discovered that in a closed circuit formed by two conductors of different nature and subjected to a temperature gradient established by a potential difference that is proportional to the temperature differences. However, the second thermoelectric effect was observed by the physicist Peltier.

The topic of this report is about thermoelectric power generators (TEGs) and heat recovery methods. It is intended to be an introduction of TEGs through an overview of the main and fundamental principles that go into its construction, also I will discuss the heat recovery methods and efficiency of thermoelectric generators, in order to do that I will explain the Seebeck effect and Peltier effect, despite the many uses and types of the heat exchangers and PCMs in industry we will briefly review their applications in the thermoelectric generators. This report will be useful for electrical engineers as it will provide information about how to produce power. It will also be valuable for chemical and mechanical engineers since they play a crucial role in the development of thermoelectric generators, and I believe that anyone who loves innovations and designing small devices even if he is not a specialized engineer, will benefit from the information provided by this report.

The first part of this report consists of an explanation of thermoelectric generators including their structure, functions, applications and how they work by explaining the Seebeck effect and the Peltier effect, while the second part will cover some heat recovery methods, efficiency of TEGs and heat exchanger and PCMs.

I. THERMOELECTRIC POWER GENERATOR

Using heat to generate electricity or electricity to generate heat is a pretty integral part of modern life, almost every kind of power plant converts heat into electricity by boiling water to produce steam which turns a turbine that generates electricity, this generally involves some fairly complicated moving machinery, but there is rather interesting mechanism that allows for a direct and omnidirectional energy conversion which is the thermoelectric effects. Traditionally for physicist's thermoelectric effects includes three phenomena but most engineering manufacturing of TEGs depend on two phenomena, one side of the coin is generating power from heat differential which called the Seebeck effect, the other side of the coin is generating heat differential from power and that is called the Peltier effect. The dependence of these two phenomena on each other was hidden nevertheless, the interdependency was demonstrated by William Thomson, he came across coefficients that describe the Peltier and Seebeck effect, he also showed there is a third thermoelectric effect, known as Thomson effect which rules in a homogenous conductor and Contain reversible temperature variations as a result of electric current and temperature contrast. Engineers usually design TEGs without taking consideration of Thomson and this report will not explain it, but I mentioned it here, as it may be taken into consideration. Rowe (2006) admit that "Although the Thomson effect is not of primary importance in thermoelectric devices it should not be neglected in detailed calculations." (p.40).

1.1. Seebeck effect

If there are two different types of semiconductor or metal wires joined together in a loop, when we keep one end very cold and the other is very hot, there will be a current flow created inside this loop. This phenomenon was discovered by Seebeck in 1822.

Figure 1 a thermocouple is formed by the two wires.

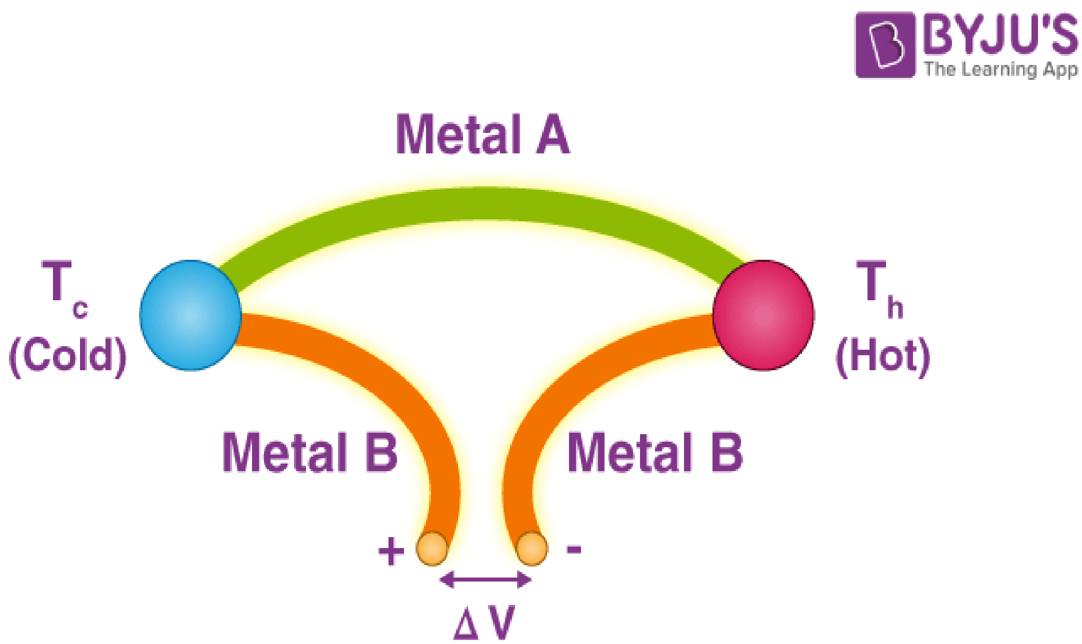


Figure 1. Thermocouple of two wires from two different metals joined at each end. Note. by Byjus (2023). https://byjus.com/physics/seebeck-effect

As it is illustrated in Figure 1 a thermocouple is formed by the two wires. If we made a connection between two different wires such as gold and silver, and the opposite terminals of the wires connected to sensitive voltmeter, when we are applying heat in the junction between these wires, we will notice a slight voltage recorded by the voltmeter. But how is this possible without current source in this circuit? let us go bottomless and comprehend Seebeck effect, the fact that is the wire made of a metal, therefore it is a conductor and that is mean it has free electrons which are capable to travel around under voltage potential difference, but at the same time we know that these electrons have a thermal energy , at the temperature of absolute zero these electron are stationary, but the higher is the temperature they start vibrating more and more having more thermal energy ,so conceive for example the wire is at 20 degrees Celsius and all the electrons inside are vibrating with the same energy ,but when we heated one end of this wire that means the electrons on this side will quiver a little bit more since they have more thermal energy , that will make the electrons more separated because now they vibrate more, so in one side we will have fewer electrons as they are further away one from each other, but in the other side the electrons are get pushed, and we will have slightly more electrons, and this causes a voltage differential since we have a deficit of electrons of the one side and more electron on the other side creating a certain positive potential on the one side and the negative one on the other side. It's quite clear that different metals will have a different amount of free electrons and this will require different amounts of thermal energy to start vibrating more and more, that is why we use two type of metal alloys, that is how we produced a current on the wires when we present a temperature difference between the two end of the loop with two different alloys.

Equation (1) shows the relationship between the voltage V of this thermoelectric generator, Seebeck coefficient S, and the temperature difference between the two ends of the junctions.

$$V = S(T1 - T2) \qquad (1)$$

The issue is the voltage value in this experiment is very low, and we can't really use it with any device. Rowe (2006) stated that for small temperature difference the relationship between Seebeck coefficient and voltage is linear and more often is measured in μ V/K. (p.39).

Equation (2) shows the current generated in this TEGs when connected to the load.

$$I = V/(R + r) \qquad (2)$$

Where R is the load resistance, r is the internal resistance of the thermocouple, (I) is the current.

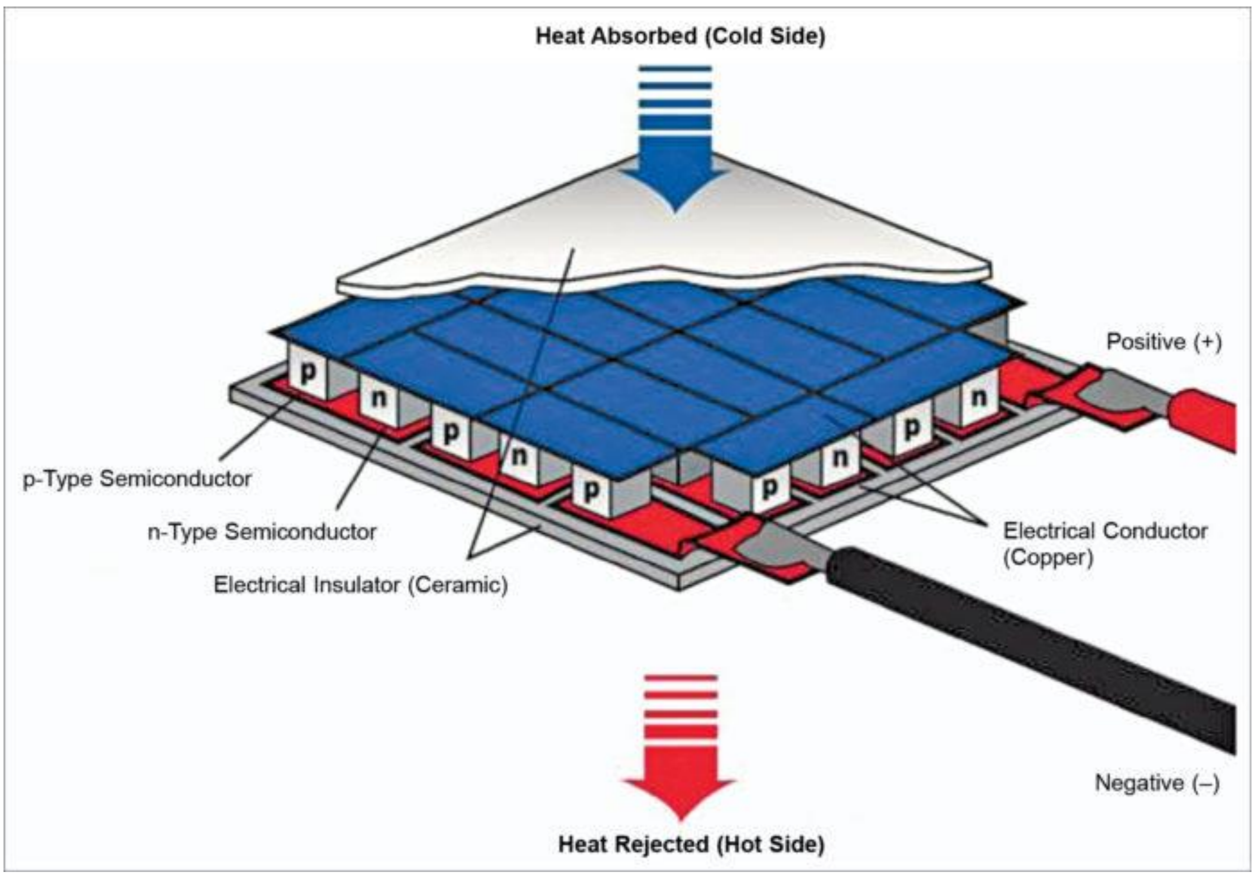
According to (1) and (2) we can describe the power generated in the thermocouple by Equation (3)

$$P = IV = \frac{S(T1 - T2)^2}{R + r} \quad (3)$$

1.2. Peltier effect

Peltier effect is the reverse effect of Seebeck effect, when we apply a voltage difference to wire loop a temperature difference will be produced, one side will become very hot, and the other side will get very cold, so we can use Peltier modules to cool down something, or we can use it backward and create voltage.

Figure 2. Cutaway of a typical Peltier cooler.



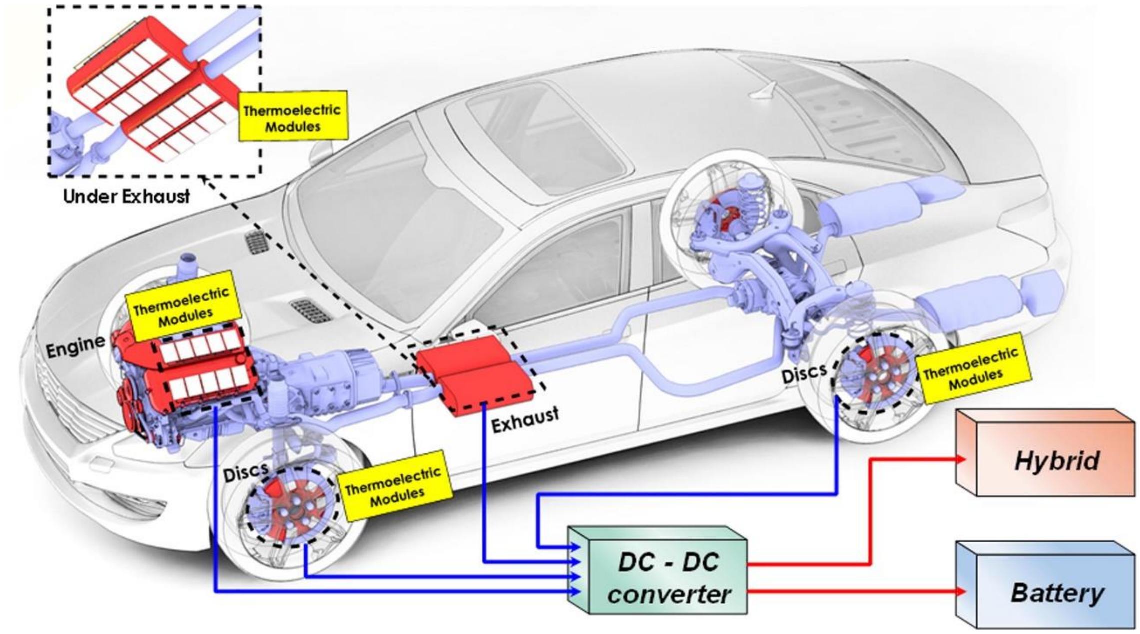
Note. Adapted from D.M. Rowe (2006). Thermoelectric Handbook Macro to Nano. (p.48).

As illustrated in Figure 2 we have in inside a Peltier cell a bunch of different metal alloys connected in series this is made in such a way that on the one side we have one alloy, and on the other side we have the other alloy, so one side will catch hot, and the other one will get cool. There are some manufacturers who made their own portable freezer out of Peltier modules and a heat dissipate and some batteries. By having a simple wire in the thermocouple we cannot create a high voltage difference, but having a lot of connections in series we can get a decent temperature difference. Lundstrom (2012) explain that if we have many of two different alloy in a device connected in series this will increase the voltage, which makes it easier to drive a large current. And the fact that they are thermally in parallel increases the power generated (P.77).

II. HEAT RECOVERY

The basic principle of heat recovery is based on the first law of Thermodynamics. Energy cannot be created or destroyed, it means the total amount of energy is constant. So when it disappears it just transforms and appears in another form, by applying the thermodynamics principles, we can recognize during the transformation of energy from one type of energy to another most of the time there are losses in a form of heat energy, and we can use this heat to generate electricity. For example, most of the energy produced by the engine in a car wasted as heat, fortunately we can use thermoelectric generator to recover the waste heat from exhaust.

Figure 3. Thermoelectric generator network and electrical system for a hybrid vehicle.



Note. Adapted from V. Abbas. (2016) et al. Measurement and evaluation of produced energy by thermoelectric generator in vehicle (p.9).

As it is presented in figure 3, the engine and exhaust canister can get hot by several hundred-degree Celsius, via put a thermoelectric generator on them, we can recover this wasted heat and turn it to electricity by Seebeck effect, and use it to power other systems in the car. Matsubara (2005) said the flow of the lost heat in vehicles take into account from technical as well as economic points of view, nevertheless there are several challenges from technical side, but it is clear that when a car is loaded with TEGs, the energy is balanced in a lifecycle and becomes optimistic in total (P.10).

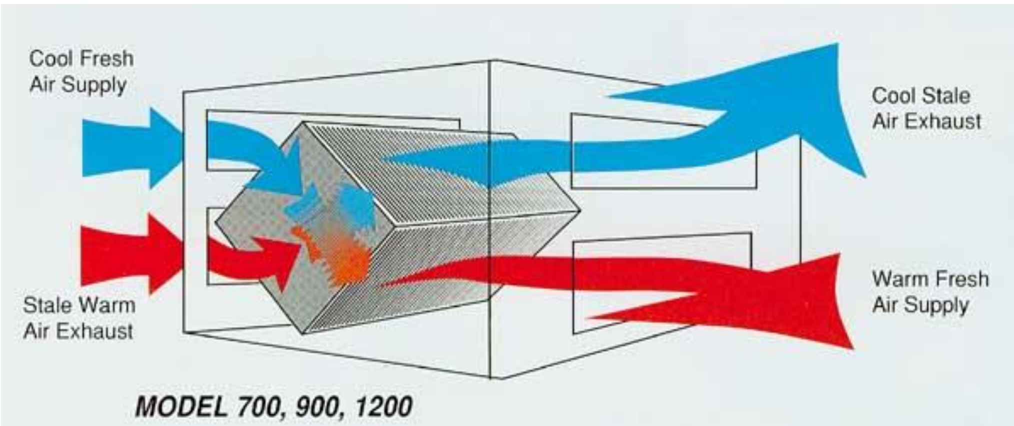
In summary, we can take advantage of using the thermoelectric generator in a lot of other systems such as the diesel engine, solar panel, industrial processes or even the human body, and covert the waste heat into electrical energy by the Seebeck effect.

2.1. Heat exchanger (HX)

The heat exchanger is a device used to transfer thermal energy, and one of its applications is in thermoelectric generators. There are many types of heat exchanger but generally all of them use the heat transfer methods, by conduction and convection and radiation.

Commonly, the HX follow one of two constructs, coil or plate, for example cross-flow plate heat exchangers (known as ducted heat exchangers) can recover the heat losses in exhaust. By exchange the thermal energy between cool fresh air and exhaust flows with no dampness transferred or mixing between fresh air and exhaust. Grysa et al. (2022), described that " The exhaust air flows through the heat exchanger without mixing with the supply air. Energy is exchanged between the air streams via plates that extract heat from the exhaust air and return it to the stream of fresh air. "(P.1).

Figure 4. Cross-flow plate heat exchangers



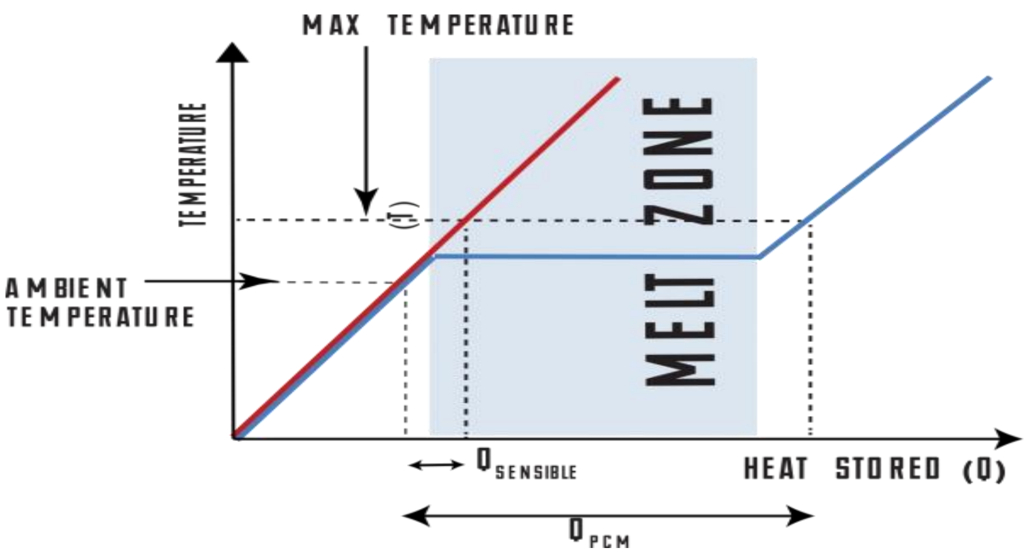
Note. Adapted from Iklimnet. (n.d). HEAT RECOVERY Fixed-plate exchangers. Retrieved December 1, 2023, from https://www.iklimnet.com/expert_hvac/heat_recovery_plate.html

As it is shown in figure 4, a type of heat exchanger formed from tiny sheets of metal with flows of different temperatures in across from diagonal paths. We can use this cross-flow plate heat exchanger in a thermoelectric generator by connecting the two junctions of the TEGs to air streams. The benefit from using this cross-flow plate heat exchanger is that can recover the heat losses in exhaust, however the downside of this type is the heat transfer efficiency it could be less than other type of heat exchanger.

2.2. Phase change materials (PCMs)

PCMs operate using a phase change. In most cases, from solid to liquid phase. But how does that happen? During the phase transition, material's latent heat grows for a limited period of time.

Figure 5. Temperature Rise vs Time. Temperature is maintained during phase transition.



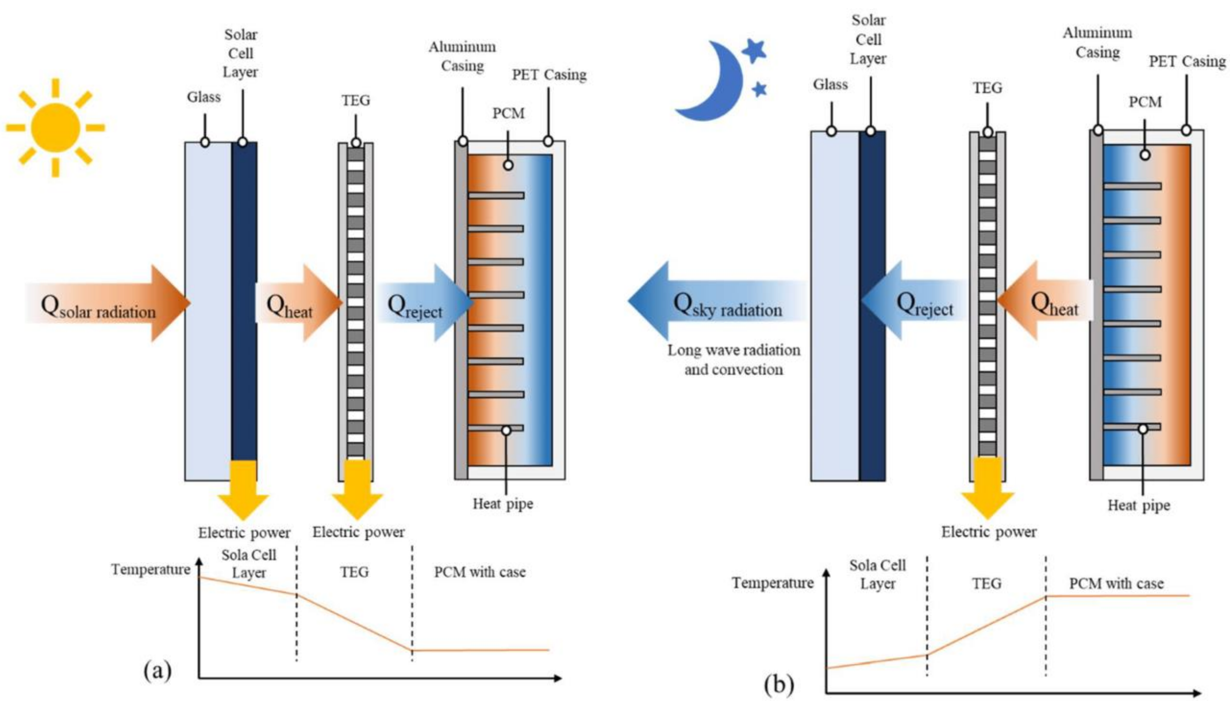
Note. ACT. (n.d.). PCMHeatSinks.RetrievedDecember1,2023, from https://www.1-act.com/thermal-solutions/passive/pcm/heat-sinks/

As it is illustrated in figure 5, in this phenomenon temperature rises on one axis and heat stored on the other over time through steady state condition. This gives a rise to many benefits, such as the provisional heat storage, also it can service to reduce weight of metal heat sinks. The main value of using PCMs is that it will maintain its melting temperature through the phase change.

Based on the amount of the PCMs in the system and the heat being applied on it, the heat sink storage capacity can be few hours. But few difficulties that need to be mentioned are the very low thermal conductivity of PCMs, beside the relatively high cost of high purity long-chain hydrocarbons. Kang et al. (2022) explained that the thermoelectric generator is a semiconductor and has a greater thermal conductivity than the PCMs. (P.9).

As I mentioned early in this report, to generate power you have to create a temperature gradient between the two junctions of the TEGs. One of the challenges is when you want to use the sun as heat sources in a wireless system, here PCMs come into the picture, and it can be used to enhance the efficiency of the thermoelectric generators.

Figure 6. Operation of thermoelectric generators enhanced by PCMs during the day and night.



Note. Adapted from Kang, Y.K., et al. (2022) Numerical Analysis of a TEGs and PCMs Enhancement System for BIPVs Using CFD (p.9).

As it is displayed in figure 6, a solar thermoelectric generator uses PCMs to maintain the temperature gradient from the radiation even at night taking advantage of the heat sink storage.

CONCLUSION

This report has discussed thermoelectric generators and heat recovery methods. I tried to explain how thermoelectric generators work, hence I have clarified thermoelectric effects such as Seebeck and Peltier effect. In addition, I have shown how thermoelectric generators used to recover wasted heat, and I have given examples of some heat recovery methods such as heat exchanger and phase change materials. These examples show that we can generate electricity without complicated moving machinery by interesting mechanism that allows for a direct energy conversion and I think the most gorgeous things about thermoelectric generators are their ability to combine with other systems and recover wasted energy. Therefore, thermoelectric generators are reliable source of electricity.

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