Mini Review of Thermoelectric and their Potential Applications as Coolant in Electric Vehicles to Improve System Efficiency

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Mini Review of Thermoelectric and their Potential Applications as Coolant in Electric Vehicles to Improve System Efficiency

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Abstract: Thermoelectric is a phenomenon of the temperature difference conversion into electrical energy or vice versa. The phenomenon has been developed into a module so that it can be used as a power generator or as a cooling/heating device. The use of thermoelectric can be further expanded as a system for generating small electrical energy and as a component for compact cooling and heating. If a unidirectional voltage is applied to the thermoelectric module, a temperature difference occurs between the two sides of the module. The cold side can be used as a cooler and the hot side can be used as a heater. Thermoelectric refrigeration technology has been applied in various applications such as beverage coolers and electronic coolers. However, the application of this technology in the vehicle still needs attention because it has good potential. Reviews relating to the application of thermoelectric cooling in vehicles are still not widely discussed, especially in terms of vehicles such as the performance of electric motors and braking. So, in this study, the use of thermoelectric as coolants in large components such as cooling in electric vehicles and braking components are discussed. Basic knowledge of the history, characteristics, performance of thermoelectric are also covered. Studies that had been carried out in several reported topics prove the potential and reliability of thermoelectric.

Keywords: Thermoelectric; Cooling System; Electric Vehicle; Braking System; Efficiency

1. Introduction

The use of various electronic components is increasing along with the increase in human creativity. The problem that commonly occurs in electrical components is the emergence of excess heat. The use of electrical components has grown so in-vehicle used. The use of thermoelectric can increase efficiency. Thermoelectric (TE) is a phenomenon in which a voltage difference can produce a temperature difference and vice versa. The thermoelectric cooling effect was found by Jean Charles Athanase Peltier, in 1834. The thermoelectric cooling or the Peltier effect is a cooling effect that occurs in the connection of two different materials that given an electric voltage/current[1–4]. The thermoelectric can be a small plate as shown in **Fig. 1**.

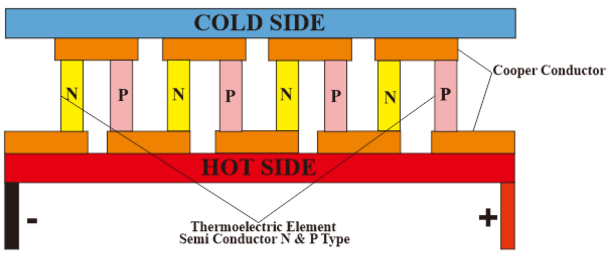

Fig. 1: Thermoelectric Components

Figure 1 shows the flow of electrons from the P-type semiconductor has a lower energy level, absorbs heat in the cooled part, and then flows to the N-type semiconductor through the connecting conductor whose surface (Tc) will experience a decrease in temperature. The heat absorbed will move through the semiconductor with the electrons move to the hot side of the module (Th). In ideal conditions, the heat absorbed on the cold side, the heat will be released on the hot side is offered on the

Peltier coefficient and the electric current used. The heat absorbed will be affected by the temperature gradient and the material conductivity. So, any conditions the thermal equilibrium that occurs due to the Peltier effect on the cold side will be equal to the amount of heat formed in the semiconductor added to the heat of 1 ½ Joule. Apart from its relatively small size, the thermoelectric module has other advantages, such as no moving parts, easy maintenance, has a lifetime of up to 100,000 hours, not contain chlorofluorocarbons (CFCs) or other ingredients that require periodic additions, and available for small application.

The use of thermoelectric currently can be covered in many areas, for example, military technology, power plant, commercial and industrial equipment space. For deeper example in the power generation, there is always losses which is heat, whether from turbine, generator, pump and pipe[5-10].

The use of thermoelectric as coolants has been studied several times but most of them are still limited to small-scale applications. The use of thermoelectric can be in the form of applications as a cooling system on a processor[1,2]. The use of thermoelectric provide an opportunity to maintain and convert the heat energy generated by the processor into usable electrical energy, as well as in extreme situations it can be used as a forced cooler when the processor is too hot. The use of thermoelectric on a larger scale can be used as part of a refrigerator as shown in **Fig. 2** Its use can be a solution for a refrigerator without using refrigerants[11,12].

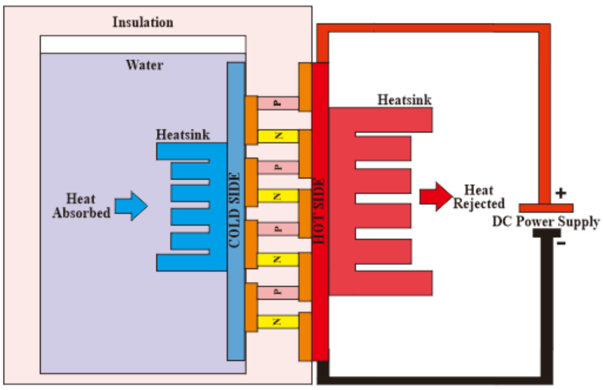

Fig. 2: Refrigerator Using Thermoelectric

Recently the Electric Vehicle (EV) widely used as transportation such as Electric Motorcycle, Car, Bus, etc. To ensure the safety of the driver and passenger, those vehicles need good braking system, which has good and efficient braking force. Due to frictional in braking process there will be high temperatures that reduce the braking force therefore, to maintain the temperature in braking mechanism there is potential of thermoelectric as coolant can be used.

This study will discuss about History and Basic Theory in section 2, Thermoelectric as Cooling in The Vehicle in section 3, Thermoelectric in Other Application in section 4, and Summary in section 5. The aim of this study is strengthening scientific information about potential of Thermoelectric for cooling application in Electric Vehicle, which is still rarely discussed and implemented.

2. History and Basic Theory

2.1 Thermoelectric History

Thermoelectric nominees were originally discovered by a German physicist named Thomas Johann Seebeck in 1821. Seebeck observed that if there are two different materials connected at the ends, then one end is heated, an electric current will flow. This phenomenon is called the Seebeck effect. In 1834, the opposite was discovered by Jean Charles Athanase Peltier. When an electric current flows in the connection of two different conductors there will be an event of heat absorption (cooling) or heat dissipation (heating). It is called the Peltier effect. Apart from the Seebeck effect and the Peltier effect, there is one more phenomenon, namely the Thomson effect[13]. This phenomenon is an event of absorption or disposal of heat when an electric current flows in a material with a temperature gradient. The Thomson effect is often overlooked because it is very small compared to the Seebeck effect and the Peltier effect. During the world war and after, the thermoelectric phenomenon was studied to be used in technology, especially in power generation and cooling systems. In the 1950s, generator efficiency could reach 5% and as a cooling system, it could reach temperatures below 0˚C. It has led the industry to start looking at this technology. At this time many think that thermoelectric can replace conventional technology. In 1949, Abram Fedorovich Loffe developed a thermoelectric theory based on the concept of the merit figure. Loffe's research using certain doping semiconductors as thermoelectric elements resulted in a high figure of merit. These materials are now known as Telluride, Bismuth, and Lead. Thermoelectric modules usually consist of many junctions of different materials. Therefore, the cooling/heating effect can be used for several purposes. Likewise, as a power plant, the electrical power produced can be detected and can turn on small power consumption electronic systems[14].

2.2 Thermoelectric Principle

Each thermoelectric module used for refrigeration applications is characterized into several usage parameters which determine a more accurate module selection among the many available module options. Some of the parameters that form the basis for selecting a thermoelectric module include: 1. The amount of heat that will be absorbed by the cold side of the module; 2. The temperature difference between the hot and cold sides of the module when operating; 3. The electric current used by the module; 4. The electric voltage used by the module;

and 5. The highest and lowest temperature environment in which the module operates[15–19].

As a heat pump, the thermoelectric module will absorb heat from one side and flow to the other side. In thermoelectric coolers, this will be the key to reach a lower temperature on the cool side of the module. Passing heat from the hot side naturally, without the aid of an attachment is not a good idea in a thermoelectric cooler if the target is to get a lower cooler side temperature. Several tools can be used to help drain heat from the hot side of the module, including heat sink and heat pipe[20–24]. A good heat sink should have a low thermal resistance value[25–29]. It is because the ability of the heat sink to distribute unwanted heat and prevent overheating will also determine the value of the coefficient of performance (COP) of the thermoelectric cooling system[30]. Heat pipe technology has previously been widely used in the field of aerospace equipment technology[30–34]. Heat pipes have a very high thermal conductivity value, when compared to other metals heat pipes have a thermal conductivity value hundreds of times greater. With this characteristic, the heat pipe can transfer heat with a smaller decrease in temperature along the heat pipe[23,37–40].

2.3 Thermoelectric Performance

At no load (the RL load is not connected), the open circuit voltage measured between points is[15]:

$$V = \alpha \Delta T \qquad (1)$$

Where V is the output voltage of the pair in volts [V], a [V °C – 1] - Seebeck's mean coefficients, and DT [°C] - temperature differences between partners.

$$\Delta T = T_h - T_c \qquad (2)$$

With Th [°C] is the hot side of the pair and Tc [°C] the cold side of the couple. When the load is connected to the thermoelectric pair, the output voltage (V) drops because of the internal generator resistance. The current through the load is:

$$I_{load} = \frac{\alpha \Delta T}{R_c + R_L} \qquad (3)$$

Where I_{load} [A] is the output current of the generator, RC [W] - the average internal resistance of the thermoelectric pair, and RL [W] - the load resistance. The total heat input to the pair (Q_h) is:

$$Q_h = \alpha T_h I - 0.5 I^2 R_c + K_c \Delta T \qquad (4)$$

Where Q_h [W] is heat input and Kc [W °C – 1] pair thermal conductance. Most TEGs contain several individual modules which may be electrically connected in a series, parallel, or series / parallel arrangement. Typical generator configurations are illustrated in. This generator has several NT modules with several modules connected in a NS sequence, and several modules connected in a parallel NP. The number of modules in the system is:

$$NT = NS\ x\ NP \qquad (5)$$

The equations can be used as a basis in determining the use of TE. By considering these circumstances, the use of TE in vehicles will be very possible[32,41–45].

3. Thermoelectric Cooling System Applications in Vehicle

This section will discuss thermoelectric implementation in vehicle as cooling system, thermal management system, or power generation. Some important studies are highlighted in Table 1, based on the implementation area in vehicle.

Table 1. Research finding comparison thermoelectric implementation in vehicle

Author	Thermo Electric Implementation
Budiyanto et. al. (2021)[48]	USV-Indoor Temperature
Abassi and Tabar (2020)[26]	Hybrid Car-Disk Brake
Nishanth et. al. (2017)[72]	Gas Turbine Engine Exhaust
Lyu et. al. (2021)[59]	Battery Pack for EV
Imonen et. al. (2021)[74]	Battery Pack for EV Thermal Management
Mocera et. al. (2018)[75]	Battery Pack for EV laboratory experimental
Li et. al. (2019)[78]	Battery Pack heating in low temperature condition

Electric motors are quite popular in various applications, such as vehicles. Electric motors can be said to be quite perfect in vehicle traction because they have very high efficiency and high-power density[42]. The electric motor is perfect for downsizing a vehicle model and can produce maximum torque at low rotational speeds. Motor failure can result in a large loss of income. Therefore, the calculation of losses in induction motors is very important, because it directly affects the overall motor efficiency and temperature distribution. The uncertainty associated with the determination of thermal losses and coefficients becomes a problem in predicting the temperature distribution. In determining efficiency and temperature rise, as well as engine ratings, these losses play an important role. Several factors are very influential in decreasing the performance of electric motors, such as temperature[46–49].

The temperature to which it is exposed determines the operating point of the permanent magnet. Losses in electric motors can occur because of changes in the magnetic field. This is related to the distribution of the magnetic field inside the motor, the magnetic flux density in the air gap and the changing core[50,51]. Thermal conductivity, copper core resistance, permanent magnet remanence, and intrinsic coercivity can change with increasing temperature[52,53].

To overcome this, a cooling system is needed so that the performance of the electric motor can be maintained properly[48,54,55]. Several electric motor cooling technologies have been developed and one of them is the thermoelectric cooler. Budiyanto et. al. has conducted a study that discusses thermoelectric cooling in unmanned vehicles. In his study which aims to analyze the application of a thermoelectric cooler to control the room temperature of an unmanned surface vehicle to keep it stable. To achieve this goal, a prototype 12V thermoelectric cooler was created and tested on a 1.5-meter unmanned surface vehicle. Budiyanto et. al. showed that the thermoelectric cooler was effective in reducing the indoor temperature of the unmanned surface vehicle to 19.5°C[48].

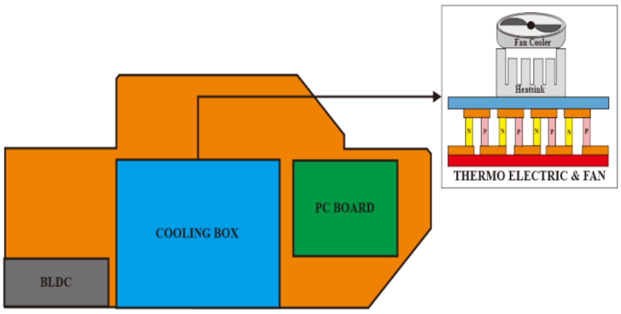

Fig. 3: General arrangement of electronic and cooling system of the designed USV

A similar study conducted by Li et. al. examines thermoelectric coolers for thermal management of lithium-ion battery modules. In his study, the discussion was carried out on battery modules used for electric vehicles. The discussion is not directly focused on electric motors, but is still in the same scope, namely electric vehicles. The combination of thermoelectric generator (TEG) and forced convection (F-C) designed as an effective and feasible cooling system for battery thermal management system is reported. For this purpose, Li et. al. conducted a comparison on natural convection cooling, F-C cooling, and TEG cooling. The results show that TEG cooling is better than the other two coolers. The TEG cooling system is proven to be able to reduce the temperature by 16.44% at 3C discharge[24,39,56–59]. The TEG-FC cooling system can reduce energy consumption compared to the other two TEG-based cooling systems.

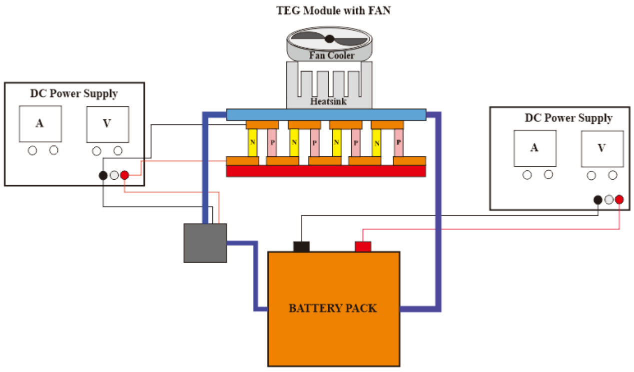

Fig. 4: Schematic of thermoelectric cooling system on battery pack

Based on the studies that have been reported, the thermoelectric cooling system has proven to be quite effective in electric vehicle applications. The use of thermoelectric cooling systems was also reported in several other case studies. This indicates that thermoelectric cooling has reliable potential in electric vehicle applications. In addition to the application carried out on vehicles, this system is also developed and reported in a case study of the braking system.

The function of the braking system in transportation is to slow down the speed of the moving vehicle or make it stop in the shortest distance possible whenever needed, braking system that is widely used is friction brake, where the braking system used uses the principle of friction[60]. A braking system produces frictional work associated with high temperatures causes the brake fluid to boil and causes gas resistance and reduces braking force[24]. Therefore, to maintain braking performance, an effective cooling system is needed. One of the cooling technologies developed for this case is cooling with a thermoelectric module.

Hsueh conducted a study that discussed the application of a thermoelectric cooling module in vehicle braking systems. The study aims to prevent high temperatures that rise due to braking force for a long time[61–64]. The modules implemented include a disc brake system and a drum brake system. A cooling surface that adheres to the brake system and absorbs heat from the brake pads or shoes is provided by the thermoelectric cooling module after applying electric power. The other surface releases heat which is absorbed by other cooling systems. The results show a decrease in the working temperature of the brake system up to 30% after using a thermoelectric cooling device. In addition, an increase in braking force of about 30% is generated because of the cooling. The thermoelectric cooling module starts to work when the temperature of the brake pads or shoes exceeds 50°C. This device is reported to be very efficient in maintaining the braking force when the driver uses the brakes for a long time and provides safety for the driver[26].

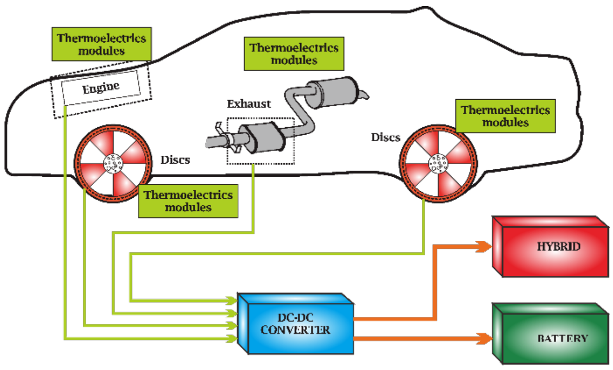

Fig. 5: Illustration of thermoelectric cooling system network on hybrid car braking system

There is another common vehicle braking system which is Eddy Current Braking (ECB). According to Putra et. al. ECB is an electromagnetic brake that uses the principle of eddy current, which is produced by the induction when the rotor rotates due to the magnetic field produced by the stator[65,66]. With this Eddy Current existence not only can be used for ECB but also supplying energy to the thermoelectric as cooler.

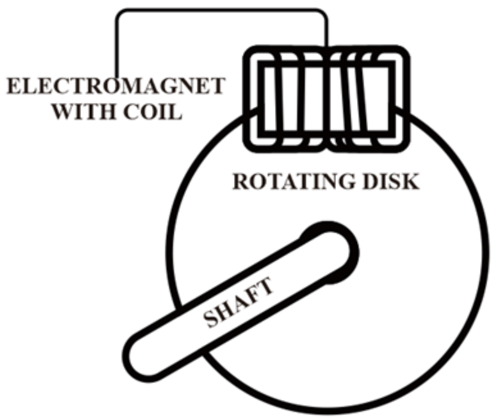

Fig. 6: Axial Eddy Current Brake

Some studies showed that thermoelectric generators is applicable in automotive especially in the heat waste of exhaust, the internal combustion engine exhaust heat exchanger is attached to the thermo-electric generator assembly for potential heat transfer, the corresponding output voltage and power value is achieved using thermo-electric generators[51,67–71]. Nishanth et. al. also conducted the research energy harvesting using Quantum Well Thermo Electric (QWTEG) materials Generator in the Gas Turbine Engine Exhaust, the result showed utilizing waste heat and converting it into electricity increases the efficiency of battery, the power output from QWTEG is about 11.3 KW for both engines of an aircraft[72,73]

For Electric Vehicle (EV) application thermoelectric also used as thermal management for the battery. Immonen et. al. conducted study the usage of Thermo Electric for thermal management Lithium-Titanate Oxide battery cell in different temperatures. They modelled an Incremental thermoelectric CFD for discharging condition for an electric rallycross car prototype[74]. Mocera et. al. also did study and identification of the thermoelectric behavior of Lithium-Ion batteries for electric vehicles, they created a laboratory testing system for observing the temperature increasement when battery is discharging, they also uttered that battery thermal management very sensitive aspect because they can store a large amount of energy therefore the result is the thermoelectric is important for this case[74-77].

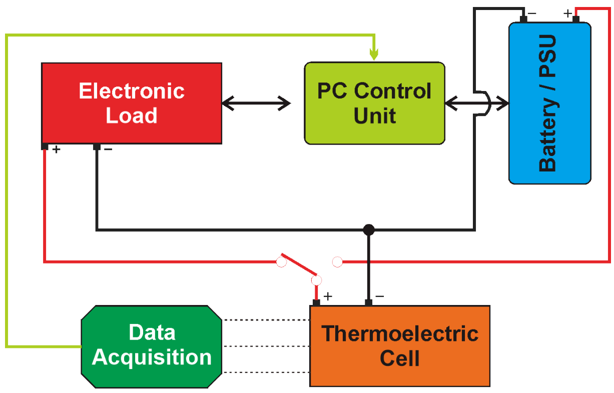

Fig. 7: Electronic load connection to thermoelectric

Li et. al. presented another application of thermoelectric for thermal management in EV's Lithium Battery, they use thermo-electric coupled model in order to gain sinusoidal alternating current heating and optimize lithium-ion batteries in low temperature condition[54,78,79]. Nizam et. al. presented study about heat management on LiFePo4 Battery Pack for Eddy Current Brake Energy Storage on Rapid Braking Processes, on 2C and 3C rate discharge battery pack's temperatures respectively are 44°C and 48°C, with air cooling implementation there will be temperature difference between battery pack and the air cooler[80]. This study strengthens the potential of thermoelectric applications on electric vehicles especially on battery pack implementation.

4. Thermoelectric in Other Applications

Several studies showed that, thermoelectric can be applied in other application. In this section some important studies are highlighted in Table 2.

Table 2. Research finding comparison thermoelectric implementation in other applications

Author	Implementation
Açıkkalp et. al. (2020)[81)]	Fuell Cell
Goma et. al. (2020)[83)]	Cement Rotary kiln
Yang et. al. (2021)[84)]	Heat Exchanger
Babu et. al. (2018)[89)]	PV System

In fuel cell application, Açıkkalp et. al. did research about comparison performance of molten carbonate fuel cell-alkali metal thermal to electric converter and molten carbonate fuel cell-thermo-electric generator hybrid systems, and the result results show that the system MCFC-AMTEC hybrid system is more advantageous than the MCFC-TEG hybrid system, maximum power output densities for the MCFC-AMTEC and MCFC-TEG are 2425.833 (W/m2), and 1964.389 (W/m2), respectively, while efficiencies are %, 76.6% and 76.4%[81)].

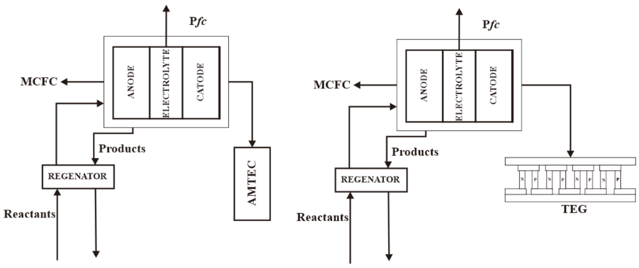

Fig. 8: Schematic of thermoelectric system in fuel cell, (a) MCFC-AMTEC and (b) MCFC-TEG

Goma et. al. conducted study application thermoelectric using for recovering waste heat from cement rotary kiln, they found that thermoelectric needs passive cooling method for enhancement the energy conversion efficiency, heat sink and fan cooler need to be added in this method, thus the efficiency can increase[82,83)].

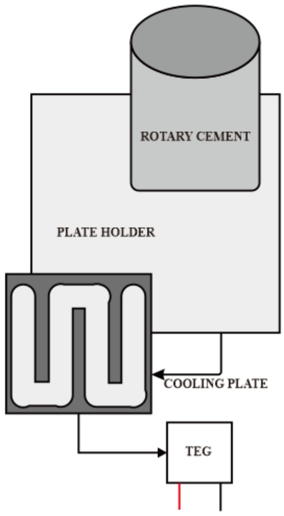

Fig. 9: Illustration picture thermoelectric application on cement rotary kiln with cooling plate

Yang et. al investigated a problem on low-grade thermal energy recovery of thermoelectric generator in heat exchanger, they design compact heat exchanger so that the modularization assembly of a TEG system can be achieved, and the TEG system can be scaled up by alternately arranging hot- and cold-side heat exchangers[30,84)].

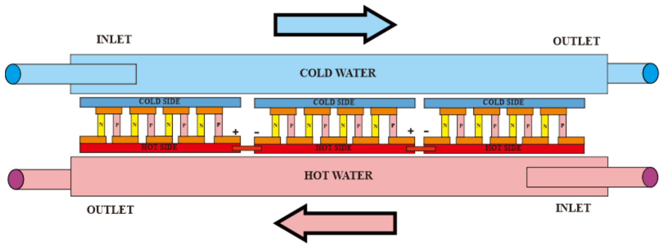

Fig. 10: Compact heat exchanger illustration with thermoelectric

Yu et. al. introduced thermoelectric which consists of two different phase change materials (PCMs); polyethylene glycol (PEG) and 1-tetradecanol (1-TD), and a cell of N and P type semiconductors by using graphene oxide (GO) which was successfully synthesized, the GNP embedded graphene aerogel enhanced the shape stability without any loss of internal porous structure. The phase transitions of the PCMs lasted for a sufficiently long period of time. Thermal conductivity of the PCM composite was increased significantly after infiltrating into the 3D porous graphene aerogels[53,85)].

Several groups of researchers had studied improving the element of thermoelectric so that it can be applied in other electrical systems, whether for electricity generation or other purposes. In electricity generation implementations, one of the example-field thermoelectric material combined with solar panel for efficiency energy enhancement and then the optimization of solar panel system can be achieved from the sun light and its heat[86–

[88]. Babu et. al. explained that by adding thermoelectric in solar panel system it can increase the efficiency for 6%[89].

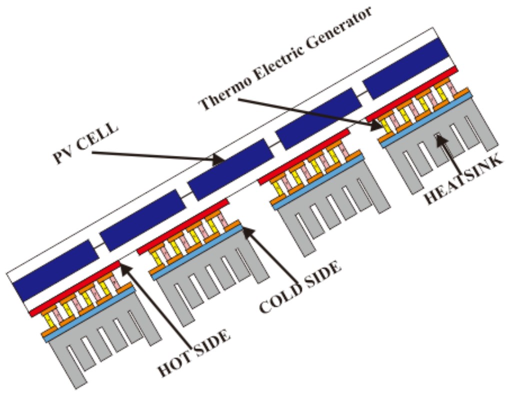

Fig. 11: TEG-PV system

Because of several thermoelectric lacks when meet a certain condition, the thermoelectric has need to be improved. Studies showed that thermoelectric quality can be improved by modelling its structure and adding some materials and then the performance and energy efficiency can be enhanced[44,90-92]. Yang et. al showed by adding three-way catalytic converter (TWC) in exhaust it can increase maximum power output 16% and net power output 37%[44].

5. Summary

Thermoelectric applications in vehicles have been discussed. Several case studies are reported showing the potential for reliable thermoelectric applications. Discussions related to the application of thermoelectric as a cooling system in vehicles and braking systems explain thermoelectric cooling system was very effective and can compete with other cooling systems. For the future suggestion of high-quality thermoelectric technology should pay attention on adding material inside the thermoelectric itself that can increase its efficiency. Potential application in vehicle especially electric vehicle, should look what is the kind of the vehicle, where part of the thermoelectric will be implemented on disk brake for braking, on motors as cooler, or on battery pack as thermal management system, and then the type of thermoelectric to be implemented can be decided.

Based on the cases those have been reported, efficiency using thermoelectric can be significantly improved. However, studies either in the form of experiments or others that investigate the application of thermoelectric in vehicles, especially as a cooling system, are still very minimal. This should be able to increase interest in the discussion of the use of thermoelectric further considering its very good potential.

Acknowledgements

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Nomenclature

COP	coefficient of performance (–)
c_p	specific heat capacity (J kg^{-1} K^{-1})
P	power (W)
$\dot{E}$	exergy rate (W)
h	specific enthalpy (J kg^{-1})
s_0	specific enthalpy of the dead state (J kg^{-1} K^{-1})

Greek symbols

δ	exergy defect (–)
η	efficiency (–)

Subscripts

2nd	Second Law
Carnot	Carnot
Dis	discharge
e	exit

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