COMPREHENSIVE STUDY ON THERMOELECTRIC PRINCIPLE, MATERIALS, APPLICATIONS AND THEIR EFFICIENCY PARAMETERS

Abstract

Environmental protection, energy conservation, and safety are some of the advantages of thermoelectric material. It's a useful substance that combines electrical and thermal energy conversion. Other characteristics of thermoelectric devices include their small size, low weight, absence of mechanical parts, vibration and noise, accuracy, dependability, and non-contamination of the environment. Because of this, thermoelectric materials have emerged as a hot topic in materials science research in recent years. Evaluation of waste heat is becoming normal in many fields like Automobiles, Industries, etc. One can easily harvest this waste heat by use of Thermoelectric generators (TEGs). As the name suggests, TEGs convert heat into electricity based on thermoelectric principles. This chapter provides an easy-to-understand explanation of the history of thermoelectrics, current research, and the thermoelectric (TE) phenomena. It also covers the uses of thermoelectrics in daily life, including the explanation of thermoelectric generators used in vehicles and bikes. An explanation of the elements affecting thermoelectric efficiency is provided, along with recommendations to enhance it. A comprehensive overview of how to choose TE material is given. This chapter covers a wide range of topics, from fundamental concepts to the most current research.

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I. INTRODUCTION

Thermoelectricity is the phenomenon of conversion of heat into electricity and vice versa based on the Seebeck, Peltier effect and Thomson effects. The temperature gradient (difference) between the two dissimilar metal junctions develops a potential difference between the ends which results in the production of electricity, this phenomenon is named after the Italian scientist Seebeck as the “Seebeck effect”. When a current passes through the loop made of dissimilar metals, a cooling or heating effect at the junctions concerning the direction of the current is observed. This phenomenon is called the “Peltier effect”. There is one more thermoelectric phenomenon called the Thomson effect. When a temperature difference is maintained between the ends of the homogenous conducting wire and upon passing electricity through the wire then absorption or releasing of heat throughout the wire is noticed.

One method of producing power is to create a converter that converts heat into electricity without the need for moving parts. Such converters were first used in the 19th century and are known as thermoelectric generators (TEGs) or thermophiles. TEG is also used to develop cooling or heating effects upon the passing of electricity and is named Peltier coolers. These TEGs have many advantages as they don’t have any moving parts, emit no harmful gases, and can be made of the desired size[1]. To date, TEG is used in automobiles, spacecraft, and Industries. They are used almost everywhere, where heat is evolved and wasted. In 1948, the first TEG was made that used the heat that evolved from kerosine lamps to produce electricity to operate radio in rural areas[2].

The first thermoelectric refrigerator (TER) was made in 1950 by a group of people organized by Ioffe at Maslakovets laboratory with flow of water as coolant. Further, more developments for the refrigerator were made, and finally, in 1954 they manufactured a refrigerator with air cooling that can be operated at a temperature difference of 60℃ to achieve -2.3℃ in the middle of the refrigerator chamber. Instead of using PbTe, a solid solution of PbTe and PbSe were used as n-type legs and $(Bi, Sb)_2Te_3$ as p-type legs. Later on, many TEGs are developed but due to the low efficiency the research in this field is reduced in favor of more efficient engines [2]. TEGs can be a future scope for waste heat harvesting as well as to produce a cooling effect as they are solid state, have no moving parts, and emit no harmful gases. (Repeated)

II. PRINCIPLE OF THERMOELECTRICS

1. **Seebeck Effect:** Most discoveries in history have been made by coincidence. The thermoelectric effect, or thermoelectricity in this instance, was one of the many accidental discoveries discovered by Volt. This effect, as its name implies, takes into account the connection between thermal and electrical energy. In the 18th century Luigi Aloisio Galvani conducted experiments many times on the effect of current on animals and finally concluded that there is an electrical imbalance exists between nerves and muscles, contraction of muscles occurs when muscles and nerves are electrically balanced. Unfortunately, He couldn’t explain well about it. Italian scientist Volta, who has been conducting similar experiments observed an efficacy. Contraction of muscle occurs when the nerve of the dead frog is connected through a bimetallic arc, this results in a conclusion that there is no requirement for the electricity to flow from inside of the

muscle to outside for contraction and all it needs is an external stimulation[3]. He noticed this special case and conducted another experiment, the legs of the frog were dipped in a glass full of water, and the spinel was set in another glass, when two glasses were short-circuited by bimetallic wire, contraction of the legs was observed.

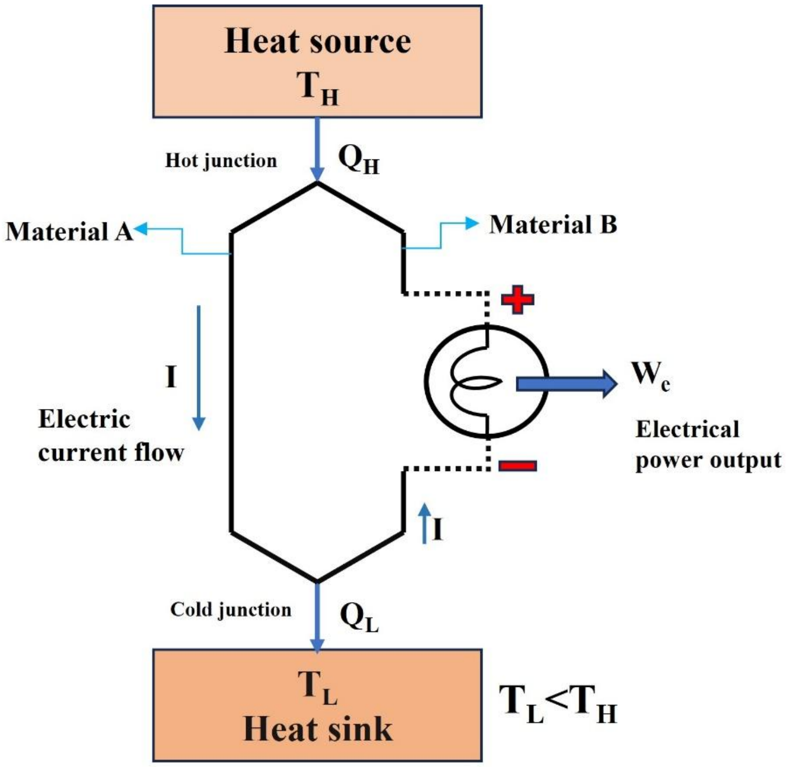

Figure 1: Schematic of Seebeck effect

Thus, by experimenting many times he concluded that to achieve a contraction, a temperature difference should be maintained between two ends of bimetallic wire (i.e. between the two glasses) which results in the production of electric current in bimetallic wire (Fig.1). This experiment and conclusion are the foundation for the thermoelectricity. After 20 years a German scientist Johann Seebeck observed a thermocouple (i.e. closed circuit made of two dissimilar metallic conductors) deflects a compass near to it when a temperature difference is maintained. This phenomenon of developing potential differences in a thermocouple due to temperature gradient is named after the scientist Seebeck as the "Seebeck effect" even though Volta first observed it. The Seebeck effect is expressed by the Seebeck coefficient given below:

$$\propto = -\frac{\Delta V}{\Delta T}$$

Where $\propto$ is the Seebeck coefficient (thermoelectric power, or thermopower), ΔV is the potential difference and ΔT is the temperature difference. The thermo power has the units of V/K, which is an important parameter of the material that gives the efficiency of a thermo electric material. The working of a thermocouple is the direct consequence of Seebeck effect, used to measure the temeprature diffrence.

2. **Peltier Effect:** Thirteen years after the Seebek effect was discovered, in 1834, Peltier found that when current is forced into a bimetallic wire, the junctions of the ends get heated or cooled depending on the direction of the current. [4]. Peltier tried to relate this phenomenon with joule heating but failed to explain/find a relationship. In 1838, Lenz a Russian physicist, proved that the Peltier effect is an autonomous phenomenon of materials and can't related to Joule's heating. Thermodynamically joule's heating is irreversible while Seebeck and Peltier are reversible. Furthermore, Joule's heating occurs due to resistance offered by the material while the Peltier effect is due to the fact that, the Peltier coefficient is different for individual materials. So obviously from equation (3), the thermal current is also different for two materials (Fig.2) and causes the difference in temperature at one junction which is supplied to another junction to maintain temperature equilibrium[5].

   Peltier effect is given as:

$$\pi = \frac{Q}{i} \qquad \text{............ (2)}$$

$$q = \pi J \qquad \text{............. (3)}$$

   π is Peltier coefficient, Q is heat released or absorbed, i is the current through the junction, q is thermal current i.e. heat, and $J$is the current density.

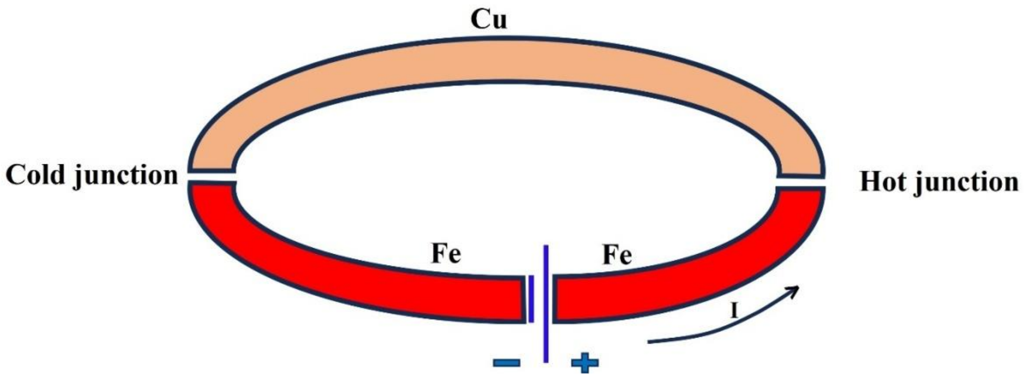

Figure 2: Schematic of Peltier Effect

3. **Thomson Effect:** Thompson's effect is also similar to that of the Peltier effect. Here in Thompson's effect, when a current flows through a conductor while maintaining a temperature gradient, heat is evolved or absorbed (Fig.3.). The heat thus generated is proportional to the current and the temperature gradient [6]. In practice, only one thermoelectric phenomenon do exist, i.e. Seebeck effect. Peltier and Thompson effect's display the manipulation of the same phenomenon.

$$\tau = \frac{q}{\boldsymbol{J}.\nabla T} \qquad \text{........... (3)}$$

   Finally, Thomson succeeded in finding the relation between the three effects:

$$\pi = \alpha T \quad \text{and} \quad \tau = T\,\frac{d\alpha}{dT} \qquad \text{............ (4)}$$

   Where τ Thomspon coefficient, q is heat absorbed or released per unit time and unit volume, and $\boldsymbol{J}$ is the current density.

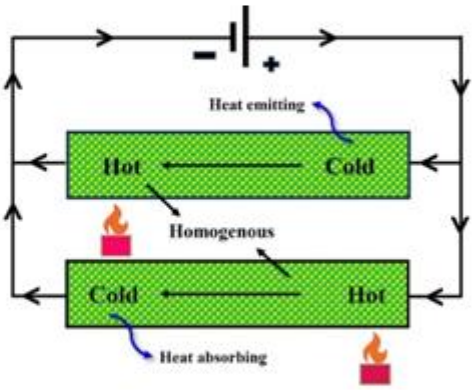

Figure 3: Schematic of Thomson Effect

III. THE FIGURE OF MERIT

If we go through the origin of the figure of merit**,** in 1909 Altenkirch, the German Physicist derived maximum efficiency for TEGs. According to him, the efficiency of TEG is the ratio of electric power generated to the heat supplied. In the same way, he derived the coefficient of performance (COP) for the Peltier effect which is defined as the ratio of heat absorbed at the cold side per unit of time to the amount of electric power utilized. Finally, he concluded that a good TE device should possess high conductivity, a large Seebeck coefficient, and low thermal conductivity. During World War Ⅱ, Abram Fëdorovič Ioffe proposed a formula to know thermoelectric conversion efficiency by assuming that the thermoelectric properties are independent of temperature, i.e. the dimension less quantity called figure of merit[7].

$$zT = \frac{\sigma\alpha^2}{\kappa}T \text{ ………………(5)}$$

Where T is the absolute temperature (K), σ is electrical conductivity (Scm^{-1}), α is the Seebeck coefficient ($V\mathrm{K}^{-1}$), κ is the thermal conductivity ($Wm^{-1}K^{-1}$). Currently, this figure of merit has become the primary parameter to compare the efficiencies of different thermoelectric materials. To obtain a good figure of merit value, one should prepare the material with low thermal conductivity (κ), High electrical conductivity (σ), large Seebeck coefficient (α), and huge power factor i.e. the product of the square of the Seebeck coefficient with Temperature (α^2T) is known to be power factor [8]. The figure of merit is the determining factor of how efficient a thermoelectric device/ generator can perform. This depends on many factors as mentioned above, although to improve zT, individual parameters should be optimized. There are two ways to increment zT, by increasing the σ *and* α or by decreasing κ.

The figure of merit zT, can be increased by enhancing the electrical conductivity of the material. Electrical conductivity is different for individual materials. Some materials do exhibit high conductivity without any modifications whereas some materials need to be modified by doping or by other methods. There may be improvement in the conductivity upon doping with p-type material, which in turn results in high zT[9][10]. By doping or adding impurity, in each case enhancement in conductivity may not be possible, this might be due to various reasons such as scattering due to impurity, etc,[11]. The occurrence of a change in the phase of the material may lead to the improvement of the Seebeck coefficient [12], [13]. From the previous reports, the Seebeck coefficient is enhanced by incorporating resonant impurity doping, preparing the material via melting reaction, and alloying the two compounds. This enhancement might be due to the changes in the fermi level and the band structure[14], [15], [16]. By preparing nanocomposite materials also the Seebeck coefficient value may be enhanced which is due to the filtering of energy due to the fine particles [17]. Some materials initially have low thermal conductivity, such materials serve as promising thermoelectric materials. The intrinsic low thermal conductivity occurs due to anharmonicity in the lattice. Also, thermal conductivity can be reduced by doping nanoparticles into the bulk material, which results in the scattering of phonons in turn decreases the thermal conductivity. As discussed above alloying, doping, etc methods can be incorporated for reducing thermal conductivity [18], [19].

This is how zT may improve. However, the parameters such as annealing temperature, synthesis route, calcination time, etc., also show an impact on zT [20][21]. The value of zT being nearly 1 represents a conversion of 6%, and an energy conversion of 30% may achieved by obtaining the zT value similar to 3. According to the data reported to date, many materials are exhibiting the zT value 1. As reported in [22], [23], [24], a value of zT achieved is approximately 2. Obtaining a good zT value doesn't mean that one can utilize it in practical applications. Sometimes the material with a good figure of merit may show complexity in manufacturing of TEG for application [25]. Finally, we can conclude that the zT value is enhancing day to day due to the sincere contributions of the researchers. A good zT value will be reported soon, and all the commercial heat engines and refrigerators will be replaced by TEGs.

IV. THERMOELECTRIC MATERIALS

There have been a lot of materials that exhibit thermoelectric effects. Metal chalcogenides, metal oxides, composites like polymer-polymer, polymer-inorganic, etc., and organic semiconductors. Choosing a material for a specific application depends on some properties such as conducting nature, temperature that they can withstand, mechanical properties, etc. Mostly high-performance material has toxic elements and is less abundant in nature.

Mainly, these TE materials are categorized as Organic and Inorganic compounds. Metal oxides, Chalcogenides, Si-based materials, and Skutterudites fall under the inorganic type. Among various materials, chalcogenides are the important class that can adapt a variety of structures. These compounds are known to contain one or more chalcogen atoms (S, Se, Te) and are less ionic compared to metal oxide counterparts. They exhibit intrinsically low thermal conductivity and the electronic conductivity can be enhanced by other processes like doping. The low thermal conducting nature of these compounds makes them a good TE material. Chalcogenides like lead-based based, bismuth-based are the most used TE materials as they exhibit better and more reliable performance compared to other TE materials.

Similarly, metal oxides are also good TE materials. When compared with chalcogenides, metal oxides are both chemically and thermally stable. Their TE properties can be varied by manipulating the structure and composition. Metal oxides are economical and eco-friendly, and can be operated at high temperatures also. Though they have some advantages over chalcogenides, they exhibit low zT, as metal oxides have high thermal conductivity. One can use the metal oxides as TE material if the thermal conductivity is reduced. The highest zT obtained for metal oxides is reported to be 2.4 for $SrTiO_3$.

Skutterudite is a mineral that occurs naturally and has the general formula TPn_3 where T is transition metal and Pn represents the elements from the 15^{th} group. The structure of the skutterudites is in a way that it optimizes the electrical and thermal conductivity[26]. The filled skutterudites (doped) have the formula $A_1T_4P_{12}$ where A stands for the rare earth or alkali earth metals [27]. Among many skutterudites, antimony-based is studied more as TE material as it exhibits high σ, α, μ and atomic mass. Skutterudites are reported to be more efficient TE material in the medium temperature range of 400-850K. Also, the carrier concentration can be controlled by the chemical composition and the solid solutions of these materials may act as both p-type and n-type semiconductors. Though these have many advantages, the major drawback is that they have high thermal conductivity. Many attempts were made to reduce the value of κ.

In organic type, as the name depicts it consists of the derivatives of carbon, hydrogen, sulfur, and nitrogen. The first interest in these materials was developed in 1977 as Heeger and co-workers reported a high conductivity for iodine-doped polyacetylene. The organic semiconductors are attracted towards them as they provide conducting nature as well as attributed with soft matter. This helps in the fabrication of flexible and lightweight electronic devices via economic synthesis routes such as melt processing or solution deposition. The conductivity of the organic semiconductors can be improved via doping. One of the important futures of these organic semiconductors, in particular conducting polymers, is that they still exhibit thermoelectric properties even when they are bent. This allows us to utilize them in wearable TEGs. Another advantage of these materials is that they have low thermal conductivity. But they should be operated in room (low) temperature as there is a chance of melting or sublimation of dopant molecules above 500K.

Every TE material has advantages and disadvantages. The kind of material you select will rely on several factors, such as operating temperature, cost-effectiveness, mechanical properties, and environmental friendliness. Here is a summary of the many material types, along with their advantages and disadvantages. A comprehensive summary of the contents can be found in the following references. [27][28].

V. APPLICATIONS OF THERMOELECTRIC GENERATORS

Thermoelectric generators (TGs) have applications in many fields such as medical, industrial, residential buildings, automobiles, aerospace, etc [29]. Mainly application of these TGs is classified into two categories based on the type of conversion which is either conversion of temperature gradient into electricity (Seebeck effect) or by providing electricity to produce the cooling effect (Peltier effect)[30]. Like in our day-to-day life, most of the energy is converted into waste heat in many areas. For example, in vehicles, 33% of combusted fuel can be put to work but the rest of the fuel is wasted[31]. In the same way in industries also much heat is wasted. To counter this, TGs can be utilized wherever the energy has been wasted and produced. Let's discuss how the TGs are implemented to convert heat into electricity or achieve a heating or cooling effect by incorporating electricity.

1. **Combustion Vehicles:** Here one of the major issues in the case of fuel engines is that, when the fuel is combusted and put to work, a part of it is converted into waste heat. Here the TEGs come into play, and their role is to convert the waste heat into electricity based on the Seebeck effect. Thus, the produced electricity can be reused for vehicle maintenance which can save up to 10% of the fuel[31] as well as thus we can reduce CO_2 emission. To mount TEGs in vehicles, some conditions need to be followed. The operating point of engines should not be changed, they should be operated near their limits to achieve significant temperature gradients, and materials used for TEGs should be economical and eco-friendly[29].

   There were two suggested places for the TEGs: Between the radiator surface and the fins (where there may be a maximum temperature difference of 80 ◦C) and on the exhaust heat system (the exhausted gasses then go through the TEGs to develop a temperature gradient which in turn produce electricity)[32][33][34]. In this application, segmented thermoelectric modules must be used since the TEG's wide temperature range requires various module characteristics. The most suitable N- and p-type Bi2Te3 for the low-temperature range (<250 ◦C), whereas n-type PbTe and p-type $(GeTe)_{85}(AgSbTe2)_{15}$ alloys are the best options for the intermediate temperature range (250–500 ◦C); finally, skutterudites (p-type CeFe3RuSb12 and n-type CoSb3) are used for the high-temperature range (500–700 ◦C) [35][36].

   - **Implementation in Cars:** BMW Group designed a prototype. As reported by Smith et al., 2021 [37], the TEG is attached to the exhaust and a part of the exhaust gas is separated by arranging two flaps, which results in the optimized flow of exhaust. The arrangement of two flops is a safety precaution to protect TEGs by maintaining optimal pressure from the exhaust gases . A 200W of output resulted with this TEG arrangement at a car speed of 130km/h and with a temperature gradient of 250°C. As reported by him at constant speeds during highway rides a maximum of 600W output can be generated by using TEGs which have the ZT value =0.85 [37]. The power output can be improved by using TE materials with a high figure of merit.

     As informed by D.T. Crane in a progress report [38], two different positions are proposed for the installation of TEGs in the exhaust line. They are the after-flange position and the pre-tube position. A higher reduction in fuel consumption after installation of TEGs is achieved in the case of TEGs installed after-flange with exhaust system insulation. To overcome the drawbacks of flat TEGs a new cylindrical-shaped TEG is designed with an internal bypass of exhaust. After successful testing on the single-engine dynamometer, the TEGs delivered an output of 125W at 600℃. When the fuel efficiency of Ford and BMW were compared, BMW showed an improved fuel efficiency of 1-7% whereas Ford represented 1-2%. They concluded that finally, they succeeded in achieving 100+ W power output with high-temperature TEGs implemented in the cylindrical design.

     Here in cars Thermoelectric are not only used to produce electricity from the waste heat, they are also used for air conditioning. By implementing the Peltier effect one can achieve air conditioning[39]. But here we are mainly focusing on the conversion of the waste heat into usable electricity.

- **In Bikes:** Nowadays most people are using motorcycles for traveling. Here also when the fuel is compressed and put into work, some of it has been wasted in the form of heat. One of the problems that we face while driving long distances is mobile or other small electrical wearables. If we install a TEG near the bike silence, we may produce electricity through which we can charge the battery as well. The principle involved here is also the same as the principle we used in earlier cases.

  As reported by Kumar P [40], a TEG namely TEC12706 is used to convert heat into electricity. Here in this work, the TEG is attached to the bike exhaust and after running the bike for several distances the heat thus produced was converted into electricity. The maximum potential difference achieved by the TEG is 1.58V at a temperature of 175℃. The generated voltage can be used to charge devices that are connected to TEG. Prince Kumar concluded that the potential developed was not sufficient to charge the battery but successfully converted the waste heat into some useful potential difference. The potential difference can be further increased by connecting a few more modules in a series connection.

  In another study reported by Omar [41], a 100 cc Honda EX5 Dream bike is used to check the viability of the TEG installed under the chassis. The readily available TEGs TEC1-12710T125 from Beijing Huimao Cooling Equipment Co are connected in different combinations such as series and parallel to compare the output in each case. The experiment is conducted by varying many parameters like the presence of a fan for cooling, engine speed, and without fan. As reported by an author they successfully converted the waste heat evolved into electricity. When connected in series, the highest achieved temperature difference, voltage, and power are 73.15℃, 3.91V, and 551mW respectively. By using a DC-DC step-up converter they succeeded in charging the mobile, mp_3 player.

  Thus, we can conclude that by using commercially available TEGs, one can convert the waste heat evolving in their bike, car, bus, etc. into electricity.

- **Ships:** Ships are also run by burning the fuels. In ships, the main engine can be the source of heat which has a high power of 8-80MW [42]. So, wherever the mechanically movable parts are present there we can observe a lot of waste heat which is evolved due to friction or radiation. In ships, though a lot of waste heat evolved, most of the heat is used to purify the water, to heat the fuel. The remaining heat may not be sufficient to produce electricity by incorporating the TEGs. Incinerators are used to burn the sludge formed by the heavy fuel. These incinerators produce almost 3% of engine power. The disadvantage of using incinerators to install TEGs is they work for a limited period only resulting in insufficient heat to produce electricity.

2. **Aerospace:** The aerospace industry covers jet engines, helicopters, and spacecraft. The first application of TEGs in space by the Voyager I space probe by NASA. The use of TEGs in space crafts is due to the need for electricity. Even though there are many ways to the production of electricity, the reason for choosing TEGs is due to their lightweight, simple design, and mainly they don’t have any moving parts [31]. Here the role of TEGs

is to convert the heat into electricity and vice versa(cooling). In space crafts to cool the electronic components, food, etc we use fans to exhaust hot air which in turn produces noise and they may be inefficient and occupy more space. Whereas refrigeration through TEGs can use less space, be noise-free, and be very compact and safe [43].

The TEGs or Radioisotope thermoelectric generators (RTGs) are mostly used in aerospace applications. In space applications, the RTGs with naturally decomposable radioactive plutonium-238 can be used as the thermal source. Upon decomposing it produces heat which is converted into electricity by TEGs. A new type of RTG is developed which is the Multi Missionary Radioisotope Thermoelectric Generator (MMRTG) which also uses radioisotopes only but is designed to operate on planetary bodies. As reported by a team in [44], An MMRTG with a life span of 14 years is designed and the power output achieved was 110W at 28Volts DC according to their report. Also, they concluded that the power generated can meet all the needs of the planetary lander.

In the case of jet engines of helicopters and airplanes the heat evolved from the engines is considered as the source of heat for the TEGs to achieve potential difference According to a study by Boeing Research and Technology, a 0.5% or more can be saved by installing TEGs for production of electricity in aircraft (A review of applications). Thus, we are not only saving fuel but also reducing the emission of CO_2 by reducing the combustion of more fuel in generating electricity. As reported in [45], A TEG module made of Bi_2Te_3 is used at the nozzle of the turbine and succeeded in producing electricity in real operating conditions. However, the power generated is very low and inefficient if the weight of the cold exchanger is considered. Meaning that the weight of the device is more than the output expected. Also, they concluded to search for alternating techniques to improve the occupancy of the modules rather than covering the entire nozzle which may impact on the engine.

Sarris et al. [46] reported a new design. They compared the power output from the three different designs and achieved a good output in the design of the Vapour chamber (VC). Unlike other TEGs, TEGs have a VC to achieve proper distribution of the heat over the entire module i.e. they act as heat spreaders, which results in greater output. They designed 1) TEG with no heat sink, 2) TEG with heat sink, and 3) TEG and VC along with heat sink, among these three the design with VC has a high efficiency of 6.27W compared to the second design. The power output from the TEG module when no heat sink is provided achieves 4.19W at 100℃ when the heatsink is provided achieves 17.69W at 100℃. The TEG attached to VC along with the heat sink shows a higher output of 28.2W at 100℃. Finally, they concluded that some dynamic air conditions are needed to install this design in real aircraft.

TEGs can be almost used everywhere, the element we need is heat, and by achieving a temperature difference we can produce electricity. In aircraft much heat is evolved by the engines, if we utilize that waste heat with the help of TEGs, we can at least reduce fuel consumption and carbon emissions.

3. **Industries:** In industries, most heat is a common by-product. In some industries, this heat is used to produce electricity employing rotating turbines by steam. But most of the time the heat is released into the atmosphere. Interest in implementing TEGs is coming into the picture as they are compact and easy to install. The principle of working of Industrial TEGs is also same as the above mentioned but there may be a small difference in the design of the TEGs.

    As reported in this [47], TEGs are implemented in the stone wool manufacturing industry. Thus, the used TEGs have hot and cold side heat exchangers namely fin dissipaters and biphasic thermosyphons. The total net production of electricity by this arrangement is 45838 W. Thus, proving that one can generate high currents with the implementation of TEGs. Similarly, Meng F [48] reported some of the observations. Here they used a model based on finite time thermodynamics and the effect of some key parameters was discussed. By incorporating this model, the output achieved was 1.47kW with 4.5% efficiency when the exhaust gas was at 350℃. The key parameters thus observed are: Rather than improving the cooling water heat transfer, enhancing the gas may improve the performance and not efficiency. Along with the gas flow in the device, the hot and cold junction ‘s temperatures decrease non-linearly.

    Among all the industries the cement industry is also on the top list for producing high temperature, energy through gas exhaust. This can be easily used and converted into electricity instead of discharging into the atmosphere. As reported by Charilaou K [49], reported a new technique instead of wasting the time of the experiment. The method thus reported is the Design of experiment, which is a schematic method used to relate the factors affecting and output of the process without performing a greater number of experiments. They concluded that the most important parameter for the improvement of output was the use of fins on the heat exchange surface, which results in the increased heat exchange area. Thus, the temperature gradient increases, and the output power also. The TEG thus proposed produced a power of 3588.6W/m^2. To achieve this the temperature difference maintained between the TEG module surfaces is 209.2℃.

    Thus, from the different examples discussed above we may conclude that TEGs can be used where there are no other conventional energy conversion systems work. Also, we can produce and use electricity at a low cost by utilizing TEGs in industrial applications.

4. **Usage in the Medical Field:** We may think that in the medical field, no waste heat is evolved and how one can use TEGs. But our body itself is a good source of heat. Here if the temperature difference between the ends of TEGs is more then more power can be evolved but to run some wearables and some electronic gadgets much power is not required. The human body can produce a power of 100W, and 525W when at rest and during physical effort respectively[50]. Here the main aim of TEGs is to provide an uninterrupted energy supply for medical appliances such as oximeters, ECGs, Glucometers, etc. These appliances use very small power to operate, if we provide that power with our body heat, one can achieve uninterrupted access to the appliance.

    In 2006, Tom Torfs designed a TEG with BiTe thermopiles. The designed TEG is of wristwatch size connected to the wireless oximeter. The output power provided by

TEG is more than 100μW. At 22℃ the power output by a normal human is more than 220μW. The minimum power required to operate the oximeter is 89μW from the generator if the measurement is done for 15 sec. In this overall application, the power efficiency is noted to be 70%[51]. Thus, one can simply use the oximeter any number of times without any fear of discharging. In 2014, Yang Yang designed a prototype that can be used to supply continuous power to the pacemaker. The commercially available pacemakers have Lithium as the power source. In this present work, they designed a clock circuit to supply power to the pacemaker from the TEGs rather than supplying directly. The prototype is designed by using a TES1–12702T125 TEG. The prototype was successfully tested on the rabbit and finally, they concluded that, to achieve a good power output to the pacemaker the TEGs should be implanted under the skin which should always be exposed, and would avoid the impact of cloths. The reason behind the implantation under the surface of the skin is to achieve a high-temperature gradient. Thus, one can simply run the pacemaker, as Implantable medical devices (such as pacemakers) use very little power[52].

In the same way, many sensors, and medical gadgets can be used by incorporating the use of TEGs. Mostly all medical equipment like glucometers and oximeter use less power so one can achieve that power by converting the body heat. So we can use them in remote areas as they don't require to be charged.

VI. CONCLUSION

In this chapter, we discussed the principles involved in thermoelectric generators, and their applications very briefly. Though Volta concluded the thermoelectric phenomenon the name was given after the name of scientist Seebeck on the discovery of the same effect in 1821. The reverse of this phenomenon is proposed by Peltier and is used to make thermoelectric coolers and refrigerators. Later on, Thompson related these two effects and introduced one more effect named the Thompson effect. Later on, Ioffe derived an expression called the figure of merit(zT) to compare the efficiency of TE material. The material with the figure of merit one or above was considered a good thermoelectric material. Between 1947 and 1960 many thermoelectric generators and refrigerators were manufactured based on the above-mentioned effects. TE effect can be observed in many materials such as Chalcogenides, Metal oxides, Skutterudites, etc. TE material has its advantages as well as drawbacks when used in application and there is a need for the development of thermoelectric materials. As mentioned above, these TEGs have many applications in Industry, Automobiles, Medical field, Aerospace, etc. More research has to be done on the development of the power factor and figure of merit of the TE materials. These TEGs can be a promising alternative method for the production of the electric current from waste heat. One can easily replace conventional coolers, air conditioners, and refrigerators with the help of TEGs.

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