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AN OVERVIEW OF THE APPLICATIONS AND PERFORMANCE CHARACTERISTICS OF THE THERMOELECTRIC DEVICES

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ABSTRACT

Thermoelectric power generation has proven to be the best technology for small scale power generation for portable power systems. Looking at the advantages of the thermoelectric power generation there is a need to review applications and fundamentals of the power generation through thermoelectric set up. Present review emphasizes mainly on applications and parameters affecting performance of the thermoelectric device, which includes materials of thermoelectric, geometry of the thermo electric material and heat source, temperatures obtained from heat source, efficiency of the heat source, efficiency of the thermoelectric device on low temperature and high temperatures, connectivity issues etc. Findings from all the points mentioned above are sorted after every point and collective conclusions are drawn at last. Future modifications/recommendations are suggested in the existing power generating systems.

Keywords: thermoelectric device, thermal performance, electrical performance, geometries, materials.

INTRODUCTION

Looking at the trend towards small scale power generation, which is used for portable systems reviews and precise suggestions are very important. Beauty of non moving parts in the thermoelectric power generation increases importance of the system at small scale power generation [1] e.g. internal combustion can't be manufactured at small scale, because of its high frictional and heat losses [1], but system which is using thermoelectric devices can be easily used to produce power at small scale because of non moving parts [2 - 9].

Fundamental principles by which electricity is produced using thermoelectric devices are Seebeck effect and Peltier effect which are explained below.

Seebeck effect

The basic principle on which the thermoelectric devices work is a Seebeck principle. Generation of electrical power output when exposed to the temperature gradient is due to the Seebeck effect [2].

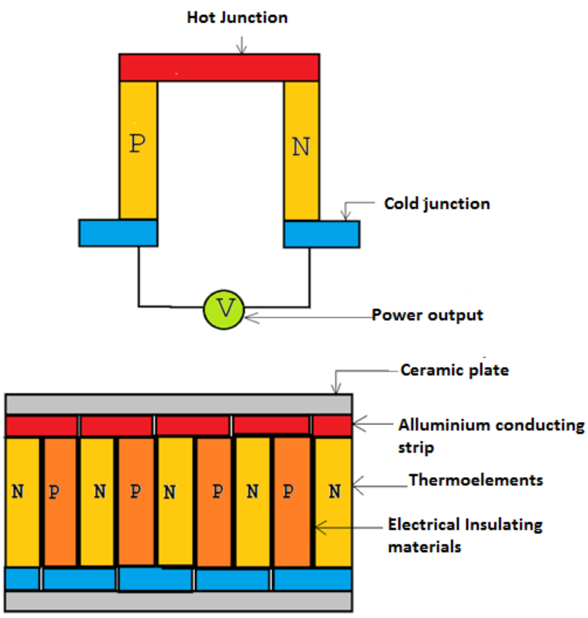

Figure-1. Seebeck effect [3].

Figure-1 explains the working principle of Seebeck effect used in thermoelectric power generation. Seebeck effect mainly works on creation of the temperature gradient between two junctions of the thermoelectric power generator. Temperature gradient is created between two junctions (i.e. one end is hot and other one is the cold end of the generator) across the thermoelectric power generator. Due to the temperature gradient and p-n junction structure in the thermoelectric generator, it generates DC voltage. Generated DC voltage is proportional to the temperature gradient. Generated voltage can be used for running various applications like

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cellular phones, small capacity fans, battery charging, micro aerial vehicles, unmanned aerial vehicles, remote sensors, divert and attitude control systems etc. Power factor of thermoelectric device is formulated as [1-5]:

$$Power\ factor = \sigma\, S^2 \quad (1)$$

Equation (1) shows the relation between power factor, Seebeck coefficient (S) and electrical conductivity (σ) [5], Materials which have higher electrical conductivity helps in generation of higher power factor which in turn helps to produce high power output [3]. Thermoelectric power generator is a power generating device whose efficiency is limited by Carnot efficiency, this is mentioned in equation (2) [3].

$$\eta_{max} = \left((TH - TC)\sqrt{1 + ZT}\right) - \frac{1}{((TH)(\sqrt{1+ZT}) + (TH/TC)} \quad (2)$$

Where, TH is hot side temperature and TC is cold side temperature. ZT here is figure of merit which is shown in equation (3) [3],

$$ZT = \frac{\left[(S_p - S_n)^2 (T)\right]}{\left[(\rho_n K_n)^{\frac{1}{2}} + (\rho_p K_p)^{\frac{1}{2}}\right]^2} \quad (3)$$

Where, ρ is electrical resistivity, T is average temperature between hot and cold sides. Equation (3) is useful when parameters related to p and n type materials are known. Subscripts n and p indicates properties related to p and n type of semi conducting materials [1].

Thermoelectric power generating device efficiency can be given as [3],

$$\eta = \frac{energy\ provided\ to\ load}{heat\ absorbed\ at\ hot\ junction}$$

Ability of a given material to efficiently produce thermoelectric power is related to its dimensionless figure of merit i.e. ZT, [3]

$$ZT = \frac{(\sigma S^2 T)}{(K)} \quad (4)$$

Where, σ is electrical conductivity, K is thermal conductivity, S is Seebeck coefficient and T is average temperature.

Peltier effect

Peltier effect describes a principle in which heat is given out or absorbed by thermoelectric device, when an electric current passes across a junction between two materials [2-9].

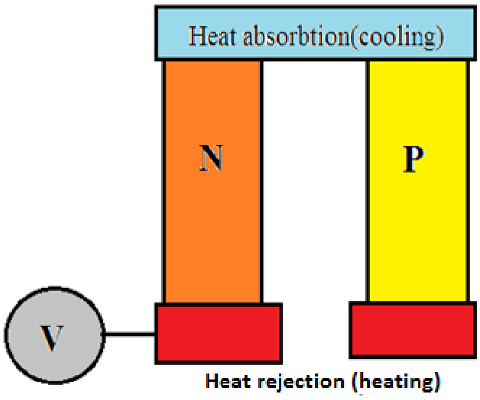

Figure-2. Peltier effect [3].

Figure-2 shows basic principle of Peltier effect for the cooling applications (e.g. Refrigeration) by using thermoelectric device. Constant voltage is supplied to the thermoelectric device as shown in Figure-2, which helps to generate a cooling effect by absorption of heat from the surface which is to be cooled.

LITERATURE REVIEW ON APPLICATIONS OF THE THERMOELECTRIC POWER GENERATOR

There are many research on applications of thermoelectric module, few of them are explained below:

A) A Russian scientist developed generator to operate radio receiver by using thermoelectric module, in which he used standard oil lamp as a heat source [6]. He used 3000 thermocouples in this design, but this was not optimized design because of low power output [6] and so he produced another generator by using kerosene burner [6].

B) Figure-3 shows miniature thermoelectric generator that was discovered in 1988 by [7] and was used to run small scale applications like charging or running a watch battery, domestic water heating component, etc.

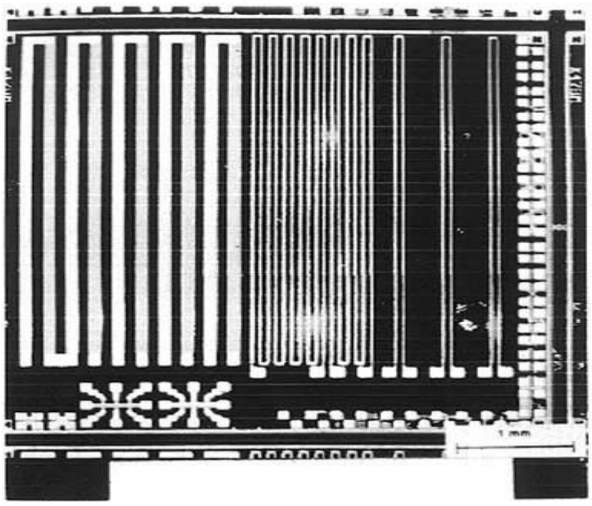

Figure-3. Miniature thermoelectric power generator photograph [2].

VOL. 12, NO. 7, APRIL 2017 ISSN 1819-6608
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C) Figure-4 shows another micro scale thermoelectric generator which is used to drive an electronic chip. This device is made up of heat conducting materials like diamond or another high thermal conductivity material [7]. In this device the Be_2Te_3 alloy is placed in thermal contact with the heat conducting substrate. The low temperature region is located at the other side. Thus a temperature gradient across the device generates electrical power [7].

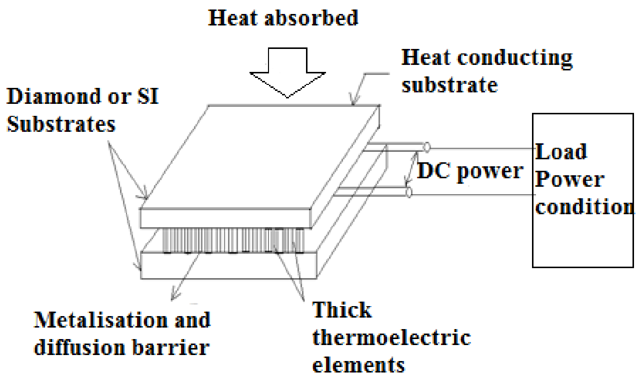

Figure-4. Use of waste heat in the thermoelectric power generator to run electronic chip [2].

D) Exhaust gases released from cars to environment can be used to generate electricity by using thermoelectric generator [32]. Approximately 30% of fuel energy is dissipated in waste heat through passenger cars running on road [2-13]. In reference [2] thermoelectric module was established by using PbTe technology which was most suitable for converting waste heat energy into electrical energy in automobiles. Electrical energy generated was used to run battery and inverter [2]. A schematic diagram in fig.5 shows waste heat energy recovery from silencers/exhaust pipes from the automobile which is converted into electrical energy through thermoelectric generator. Final power output obtained during normal working conditions of the car was 20 - 30 KW [2].

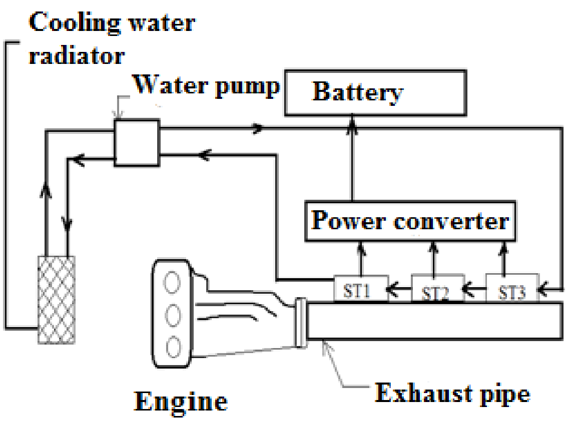

Figure-5. Schematic diagram of converting waste heat directly into electrical power using thermoelectric power generator in IC-engine [2].

Thermoelectric generator can also be used in automobile during hot seasons to cool the seats by placing the device inside the seats [2-12]. It is most simple and efficient way to add comfort inside the car, by avoiding air conditioning of car and it also saves cost [31].

E) Effect of combination of thermoelectric refrigerator (TER) and direct evaporative air cooling (DEAC) system is investigated theoretically and experimentally by [8]. Thermoelectric refrigeration system was installed mainly to improve the air cooling performance of a system [35]. The DEAC has cooling pad in which sensible heat of inlet hot air is converted into latent heat of vaporization. Thermoelectric refrigeration was used for additional cooling by supplying cold water, which improves air-cooling performance of DEAC [8]. Performance can further be increased by increasing number of stages. Figure-6 shows schematic diagram of direct evaporative air cooler.

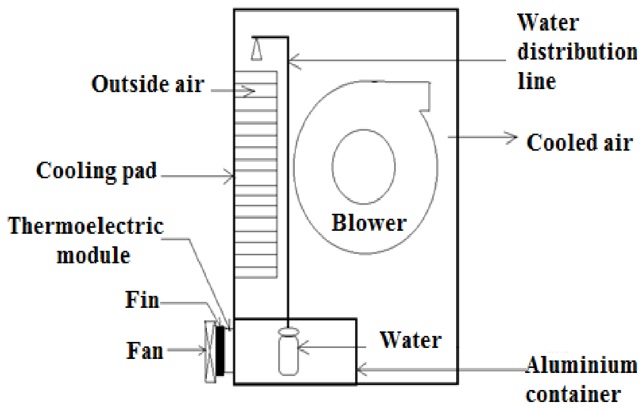

Figure-6. Schematic diagram of direct evaporative air cooler [8].

F) Thermoelectric refrigerator was developed by [7-15], which was powered by number of solar cell combined in solar panel. Solar panel gives the constant voltage and current required for thermoelectric cooler when electricity is not available (e.g. Rural areas or Deserts). Solar cells were placed as source of power supply. They generate electric current was passed through Peltier module and used to store electricity for later use [9-14]. Electricity can also be stored in batteries for further use in dark regions when there is no sun [9] or in nights. Figure-5 shows the block diagram of thermoelectric refrigerator with solar cells [30-38]. This will increase COP of the system.

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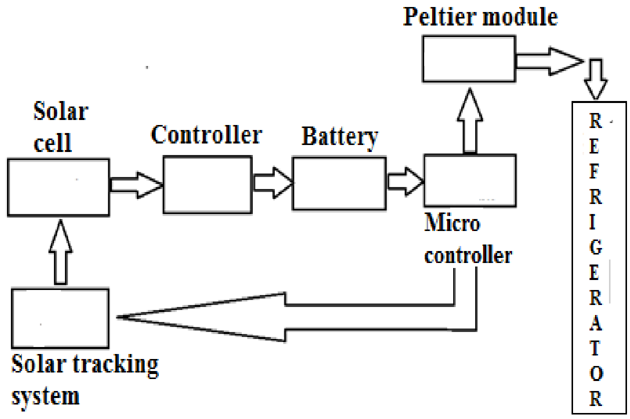


Figure-7. Block diagram of thermoelectric refrigerator with solar cell [9].

G) Medical applications describe use of temperature difference effect on treatment of various diseases in the human body. Many difficulties are faced by human body because of thermal effects which are reduced by using thermoelectric cooling system [10]. Practical applications in the areas of medicine are neurosurgery, genecology, cryotherapy, plastic surgery, dermatology, urology, oncology etc. [10]. In the dermatology, thermoelectric devices were used for stimulation of metabolism and reducing of wrinkles for the treatment of pyoinflammatory processes, freezing out of the warts, hardening of the individual parts of human body and other medical events [10].

H) Research conducted discussed that marine vessels consumes only 7% of the total energy required in the transportation [11-16]. Thermoelectric generators were used to recover waste heat energy during transportation in ships [40-46]. Because of introduction of the above thermoelectric generator system into propulsion systems reduced load on generator [40]. This hybrid vessel called hybrid “Green Ship”. Thermoelectric generator was found to be dependent on the temperature difference generated between the exhaust steam and a coolant in ship industry [11]. Many waste heat sources in ships like scavenge air cooling, exhaust gases, engine cooling jacket, lubricating oil cooling and cargo cooling were suitable for generation of electricity [11]. Mostly TEG was used for engine waste heat recovery.

Findings: Above session described use of thermoelectric generator in generating electricity by using waste heat from various systems. Thermoelectric generators use was found to be significant in following applications: automobile, aerospace, marine industry, medical applications, in refrigeration and air conditioning applications and domestic applications. Following advantages are linked with thermoelectric power generating systems: simplicity, low cost, lower weights, practically no need of device maintenance, can be used at small scale, can be used in portable systems and can be used with high energy density fuels.

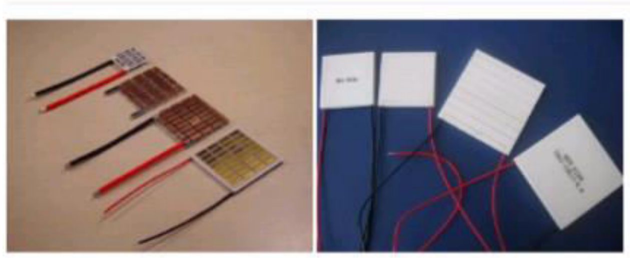
Geometries of the thermoelectric and devices

Thermoelectric devices are mainly available in two types which are as follows.

1. TEC: - Thermoelectric cooler (which is used for refrigeration applications and it uses Peltier effect)

2. TEG: - Thermoelectric generator (which is used for generating electricity by using Seebeck effect)

Thermoelectric devices are available in shape of square plate having dimensions approximate about 50 mm X 50 mm X 3 mm [3]. Dimensions can be varied according to the application. Life of TEC is nearly about 20,000 hours [3].



(a) (b)

Figure-8. (a) p-n junction arrangement (b) thermoelectric device.

Performance parameters of thermoelectric devices depend on the materials that are used as p-n junction in the thermoelectric module [49]. One example of thermoelectric device module is TEC1-12706 where silicon and germanium is used as p and n junction material. Performance data sheet is as shown in the Table-1. It is given that maximum hot side temperature of TEC1-12706 sustains is up to 50°C as well as minimum temperature required for the operation of TEC1-12706 is 25°C [50-52]. Similarly, maximum current, voltage, heat energy in watts, and temperature difference are mentioned in the Table-1.

Table-1. Performance parameters of TEC1-12706 [3].

Hot side temperature (°C)	**25°C**	**50°C**
Q_{max} (Watt)	50	57
Delta T_{max} (°C)	66	75
I_{max} (Amps)	6.4	6.4
V_{max} (Volts)	14.4	16.4
Module Resistance (Ohms)	1.98	2.30

MATERIALS OF THE THERMOELECTRIC DEVICES

As mentioned in above applications, lots of energy from industrial as well as domestic appliances is dissipated in waste heat. So there is a need of finding thermoelectric materials, which can convert waste heat into useful electrical power. That will lead to the reduction in fossil fuel consumption & CO_2 emissions [10]. The basic problem in creating efficient thermoelectric

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materials is that, they must be very good at conducting electricity but not heat [16]. In that, one end of an apparatus can get hot while other remains comparatively cold [16-19]. The main focus of research on thermoelectric materials is to improve electrical conductivity without an increase in the thermal conductivity [16]. Thermoelectric materials are associated with the issues like life, reliability of the thermoelectric device, toxicity and very less efficiency (about 5-8%) [52-54].

Thermoelectric materials such as alloys of Bi_2Te_3, PbTe, and BiSb were developed 50-60 years ago [17]. They are generally limited to use in a temperature range between 200 K to 1300 K [16]. Some thermoelectric materials such as silicides are primarily considered for their relatively low cost. Bi_2Te_3 based alloys have temperature ranges of 100^0C to 350^0C. Sb_2Te_3 and Bi_2Se_3 are the best materials to use for near room temperature [42]. For high power generation with higher temperatures Si-Ge alloys are used [33]. The efficiency of thermoelectric material is related to dimensionless figure ZT. A good thermoelectric material has high ZT value at operating temperatures [13]. The best thermoelectric materials that are currently in use in devices have a value of ZT is equal to 1 [13]. Besides that we have to look at power output. For most thermoelectric material power factor 40 is good whereas many researchers have used a power factor in the range of 20 or 30. The new material has a power factor of 106 at room temperature and researchers were able to demonstrate an output power density of 22 watts per square centimetre, which was 5 to 6 watts higher compared to typically produce in thermoelectric devices.

The Figure-9 shows relation between different material temperature and ZT value.

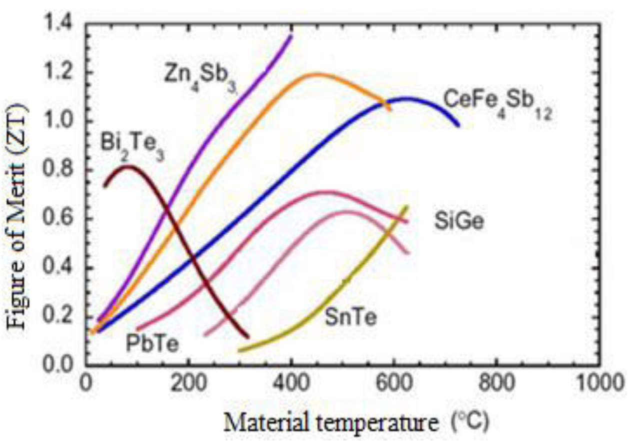

Figure-9. Relation between ZT and temperature [2].

Figure shows the behaviour of different thermoelectric materials with respect to temperature and ZT. As Temperature increases ZT also increases, but it is observed that after particular rise in temperature ZT starts to decrease. Alternative material classes are provided like nano-structured, semi conductors, and superlattice materials [10]. Materials like tetrahedrite and magnesium silicide have cost advantage over traditional material because of their low cost of raw materials [10]. Less expensive materials approach to create nanostructure in thermoelectric materials that is required if high ZT is available [10]. The most common thermoelectric material today are alloys of chalcogenides specifically, these materials are either based on Bi_2Te_3 or PbTe [10]. The new classes can allow waste heat recovery with better efficiency [10]. So it can be concluded that thermoelectric materials should have a low thermal conductivity and a high electrical conductivity. Thermoelectric materials which are employed in commercial applications can be divided into three groups based on the temperature range of operation [47]. As shown in Figure-9 alloys based on bismuth (Bi) in combination with Antimony (Sb), Tellurium (Te) are referred to as low temperature materials and can be used at temperatures up to around 450K. The intermediate temperature range up to around 850K is of materials based on alloys of lead (Pb) while thermoelectric materials employed at the highest temperatures are fabricated from Si-Ge alloys and operate up to 1300K [48].

Findings: Thus materials suitable for high temperature application are alloys of Silicon and Germanium which can operate upto temperature of 1300K.Materials suitable for medium temperature range of 500K to 850K are Bismuth and tellurium.

INFLUENCE OF THEORETICAL PARAMETERS ON PERFORMANCE OF THE THERMO ELECTRIC DEVICE

The efficiency of thermoelectric generator is the ratio of energy provided to load as electrical power to the rate of thermal energy consumption. Figure of merit ZT states the relation between electrical and thermal effects in material. Equation (4) can be used to calculate figure of merit [23]. For high efficiency generators, we have to maintain a required temperature difference between hot and cold junction. Also the material used should have high value of thermoelectric power S and low value of thermal conductivity k. For the given load maximum efficiency is achieved with a specific generator when it has low specific resistivity ρ [36-40]. Thermoelectric device is made up of p-type and n-type semiconductor. They both are considered as thermocouple. The electrical conductivity is inversely proportional to the resistivity as given in equation (7) by [6],

$$\sigma = 1/\rho \quad (7)$$

Thermoelectric power α tends to zero when carrier concentration n tends to infinity, and α to infinity when n goes to zero. But when n is reduced to zero, ρ is very large and hence figure of merit not increased, because σ is proportional to n [6]. To ensure large Seebeck coefficient, there should only be a single type of carrier [24]. For metal or semiconductor the Seebeck coefficient is given in equation (8) by [24]:

$$\alpha = \frac{8\pi^2 K_B}{3eh^2} m^* T(\frac{\pi}{3n})^{2/3} \quad (8)$$

VOL. 12, NO. 7, APRIL 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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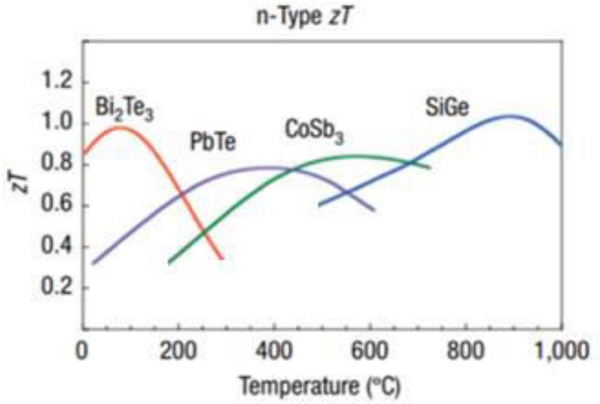
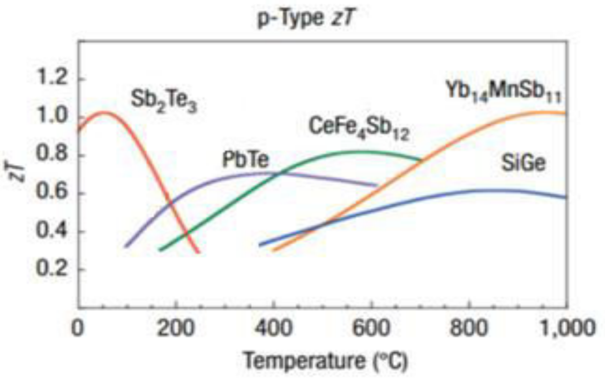
n equal to carrier concentration and m equal to effective mass of carrier. ZT increases with temperature but decreases above a certain temperature value, because of increase in thermal conductivity of material of the thermo electrics [30] as shown in Figure-6. There is no theoretical limiting value for ZT, but the best materials have value approximately equal to 1 for common use of today's material. The relation between ZT and maximum theoretical efficiency for thermoelectric element is expressed in equation (9) below [21],

$$\eta = \frac{Th - Tc}{Th}\sqrt{1+ZT}\,\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+Tc/Th} \qquad (9)$$

Where T_h and T_c are temperatures on the hot and cold sides of element respectively and T is average temperature of T_h and T_c. Hot side temperature is 250^0C and cold side is 50^0C, that increases ZT from 1 to 3 corresponds to increase in efficiency from 11% to 19% for simplest design of devices [21].



(a)



(b)

Figure-10. (a) ZT Vs Temperature for n-type [23], (b) ZT Vs Temperature for p-type [21].

Figures 10 (a) and (b) Shows the relationship between ZT and temperature for n-type and p-type material. A typical Bismuth Telluride (Bi_2Te_3) thermocouple has a seebeck coefficient of around 350 μv/κ [25]. Figure 10 explains the variation of n-type and p-type materials variation with ZT shown in two different graphs.

Findings: Parameters like temperature of the thermoelectric material, figure of merit and material of the n-type and p-type junction were found to be important parameters, which affects performance of the device.

CONNECTIVITY'S

Thermoelectric generators are solid-state heat engine made of pairs of p-type and n-type elements [28]. The p-type elements are made up of semiconductor material, which is doped such that the charge carriers are positive (holes) and Seebeck coefficient is positive as shown in Figure-11 [28]. The n-type elements are made of semiconductor material, which is doped such that the charge carriers are negative and Seebeck coefficient is negative [28]. When material is heated at one end, the atoms at the hot end have more kinetic energy than atom at the cold end [28]. For an n-type material, free electrons are able to diffuse from hot side to cold side, thereby generating a potential difference (voltage) across the device [28].

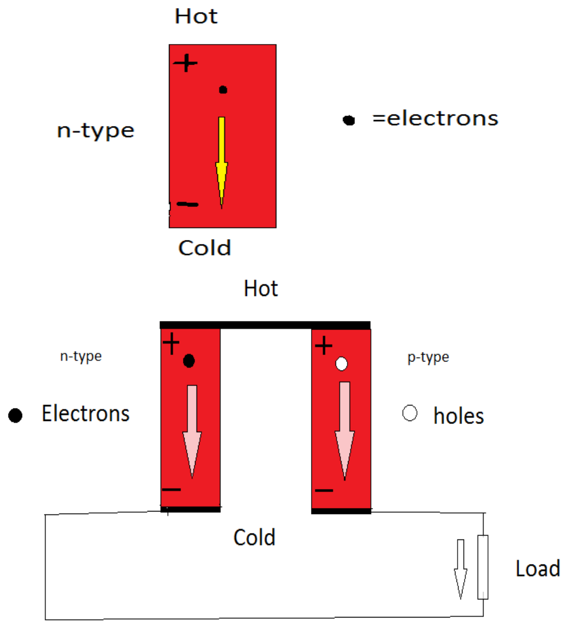


Figure-11. Connectivity of p-n junction for Peltier module [28].

A similar thing happens to a p-type material; however the sign of the charge carriers is opposite. The charge carriers in both materials, in effect, carry heat with them from the hot end to the cold end, with setting voltage at the same time. When an external circuit is connected across the n-type material; heat will be conducted away from the hot junction by the wire and electricity will not flow [20, 25, 28].

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To create a thermoelectric generator, we need to connect both the n-type and p-type material 'back-to-back' with hot junction, so that their voltage are added together, with the wires to the external circuit both connected to terminals at the cold junction, thereby allowing electricity to flow through the external circuit [20-26]. As long as there is a temperature gradient across the device, there will be a voltage given out across the terminals at the cold junction. If an external circuit is connected and an electric current flows, it will need heat to be added to the hot junction to maintain the flow of electric current [29]. So in practice, there may be hundreds of junctions connected. For improving the efficiency and power of thermoelectric generator several approaches such as, nano wires, hetero structure and super lattices using novel compel materials have been investigated with limited success [27]. Wagner et a [26] proposed use of large Si/SiGe p-n junctions for higher efficiencies of thermoelectric generator. If temperature decreases from high temperature end T_1 to low temperature end T_2, the band gap increases shown in fig. 12, because both electrons and holes moves in the same direction away from p-n junction.

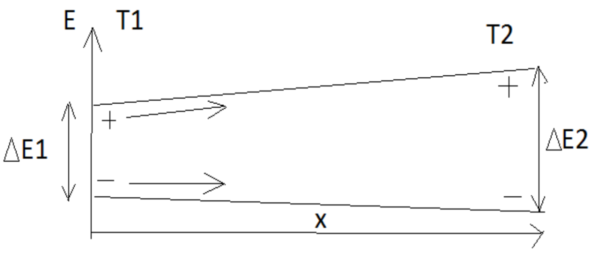

Figure-12. Temperature effect on carrier transmission and energy bandwidth [27].

If device is subjected to thermal cycling mechanical tension between two different materials may lead to fatigue. The semiconductors which have high band gap they are more suitable for high temperature application [27].

Findings: connectivity issues inside the thermoelectric device, with external heat source and overall assembly plays significant role.

CONCLUSIONS

Power consumptions and waste emissions can be reduced to a greater extent by the use of thermoelectric devices. Industrial waste heat recovery as well as domestic heat recovery applications can help a lot for reducing wastage of heat. Thermoelectric material should have low thermal conductivity as well as high electrical conductivity. Temperatures, figure of merit, material, and connectivity issues were significant parameters for maintaining required performance of the thermoelectric device. Simplicity, low cost and practically no need of device maintenance were advantages of the thermoelectric device.

ACKNOWLEDGEMENT

We would like to express our gratitude towards HOD Mechanical, JSCOE and SKNCOE for their kind support and guidance for the preparation of the review paper.

Nomenclature

Notation	Description
σ	Electrical conductivity
S	Seebeck coefficient
TH	Hot side temperature
TC	Cold side temperature
ZT	Figure of merit
S_p	Seebeck coefficient of p junction
S_n	Seebeck coefficient of n junction
P	Electrical resistivity
K	Thermal conductivity
Q_{max}	Maximum heat input
I_{max}	Maximum current
V_{max}	Maximum voltage
Bi	Bismuth
Sb	Antimony
Te	Tellurium
N	Carrier concentration
M	Effective mass of carrier
Pb	Lead
Si	Silicon
Ge	Germanium

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