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Perspectives of thermoelectric materials and devices for energy harvesting applications

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Abstract

The demand of energy consumption and requirement is increasing continuously. The increase in energy demand creates a lot of pressure on availability of conventional energy sources such as oil, gas and coal. Almost all conventional sources of energy are on the verge of extinction due to its over exploitation. There is a need of non-conventional renewable sources of energy utilization and improving the efficacy of the existing technologies. A large amount of energy is being wasted in industrial processes, power plants and automotives in terms of heat and harnessing this waste heat into useful energy using thermoelectric technology would enhance the efficiency of whole system. Thermoelectric device is a solid state device, which generates electrical energy utilizing Seebeck effect. Thermoelectric generators (TEGs) are becoming a more attractive option for power generation as these are stationary, noiseless, reliable & scalable and environment friendly. This paper attempts the understanding of thermoelectric materials, devices and perspectives of thermoelectric technology for energy harvesting and energy conservation.

Keywords: Thermoelectric Materials, Energy Harvesting, Thermoelectric Device

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1. Introduction

There is enormous increase in energy consumption in the world & it's getting hike day by day, this is a big concern of social and political unrest. Because of consumption of fossil fuels situation becoming alarming, & its impacts on environment leads to global climate change. So we have to think for improving the techniques for sustaining electricity & energy, this has been done through customising the use of electricity and scavenging of waste heat with the help of thermoelectric generators (TEGs). Home heating, automotive exhaust, and industrial processes all generate an enormous amount of unused waste heat that could be converted to electricity by using thermoelectrics generators (TEGs), as a result of that efficiency will improve significantly [1-6]. Thermoelectrics is a hot and current topic of research nowadays, owing to its potential application in industrial as well as commercial sectors. TE devices based on novel TE materials have a great potential as, power generators and Peltier coolers to be used in automobiles, RTGs, thermal sensing devices and electronic gadgets [3]. Thermoelectric (TE) modules being acoustically silent, having no moving parts hence requires a little maintenance and along with zero emission of greenhouse gases make it an attractive candidate for green energy generation. With the advent of efficient thermoelectric materials the thermoelectric power generation technology is gradually evolving as a suitable alternative to the other existing renewable sources of energy.

The term Thermoelectric can be stated as "The generation of electrical energy by the means of difference in temperature (ΔT)". Here for getting electrical energy temperature difference (ΔT) has to be maintained across some special kind of material, these special materials are known as thermoelectric materials. The materials can be either metals or semiconductors, or combination of both. A thermoelectric device is based on the concept of Seebeck effect.

When both junctions are kept at same temperature, an equal amount of electron diffuses at both of them. Therefore the currents at the two junctions are equal and opposite and the net current is zero, and if both the junctions are kept at different temperatures then diffusions at the two junctions are different and hence a different amount of current is produced. Therefore the net current is non-zero. This phenomenon is known as thermoelectricity.

TE devices consist of a number of n and p-type thermoelectric legs, connected electrically in series & thermally parallel to each other. These n and p-type TE legs should compatible to one-another. The optimum performance thermoelectric materials have been taken for synthesis of TE legs. Optimized TE legs were used for fabricating TE devices.

The Thermoelectric efficiency (η) is defined as:

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}} \qquad (1)$$

The efficiency of a TE is governed by its dimensionless figure of merit, ZT given by:

$$ZT = \frac{S^2 \sigma T}{\kappa} \ldots\ldots \qquad (2)$$

Where S is the Seebeck coefficient, σ is electrical conductivity, T is absolute temperature and κ represents total thermal conductivity. Therefore, in order to extract maximum output from a given TE device one has to increase both the power factor ($PF=S^2\sigma$) and decreasing the total thermal conductivity. These thermoelectric parameters are strongly interconnected and one cannot be decreased without altering another.

2. Materials Perspectives

Thermoelectric devices based on novel TE materials have a great potential as power generators. TE material selection plays an important role in fabrication of TE devices. The favourable thermoelectric materials should be abundance in nature, non-toxic & thermally stable with optimum thermoelectric property. Thermoelectric Devices needs to have compatible n & p-type thermoelectric legs with optimum figure-of merit (ZT). Thermoelectric generators & thermoelectric devices are desirable to operate over large temperature spam, i.e. low temperature, mid temperature and high temperature. In each temperature range the suitable thermoelectric material have to be chosen. At present the materials available for thermoelectric conversion are bismuth tellurides, lead tellurides, silicon germanium, copper selenide, silicides etc. [7-15]. Table 1: shows the various thermoelectric materials and its figure-of merit in the operating temperature range.

Table 1: TE materials with their operating temperature & figure-of merit

TE Materials	Range of Operation	Figure-of merit (ZT)
Bi_2Te_3	Low Temp.	0.9
Bi_2Se_3	Low Temp.	0.7
$Bi_{0.6}Sb_{1.4}Te_3$	Low Temp.	1.5
PbTe	Mid Temp.	1.8
Mg_2Si	Mid Temp.	0.7
Cu_2Se	Mid Temp.	1.7
SiGe	High Temp.	1.5
YbMnAlSb	High Temp.	1.3

3. Device Perspectives

A thermoelectric (TE) device converts thermal energy to electrical energy by using an array of TE legs. TE device is a solid state device generates electrical energy utilizing Seebeck effect. This device is a reliable source of power for satellites, space probes, and even unmanned facilities. Satellites that fly toward planets that are far away from the sun cannot rely exclusively on solar panels to generate electricity. These satellites will have to use an alternative energy source, such as thermoelectric devices, to generate their power. Since a thermoelectric device has no moving parts, it is reliable and can generate electricity for many years. Studies have been done on improving the efficiency of thermoelectric generator by incorporating other technologies, like nanotechnology [16-21]. By achieving a better efficiency, thermoelectric devices would need less radioactive material to produce the same amount of power, making the power generation system lighter. Less radioactive material will also decrease the cost of spaceflight launches. Although these devices are used mostly in spacecraft technologies, they can be also applied to technologies on earth, which might further contribute to the advancement of technology. Some applications of this technology include automobiles, computers, household appliances, etc. For example, thermoelectric devices can enhance the energy production of hybrid automobiles by producing electricity using the waste heat of the engine. If an environment has a thermal gradient, thermoelectric devices can be applied, since they require little maintenance, and provide electricity for many years.

4. Applications Point of View

A thermoelectric generator (TEG) or TE device consists of a p and n-type semiconductor materials known as thermoelectric legs, connected electrically in series & thermally parallel. The TEGs can be used to convert waste heat energy into useful electrical energy by using the principle known as the Seebeck effect. When heat energy is applied to one surface of the thermoelectric generator, the electrons in the n-type semiconductor and the holes in the p-type semiconductor will move away from the heat source i.e. towards cold end, produces an electrostatic potential (voltage). This movement of electrons and holes creates a path to flow of an electric current. The direction of the current is opposite to the movement of the electrons, and in the same direction as the movement of the holes. By creating the appropriate electrical contacts between both the n and p-type TE legs at the hot end, the current of the TE device flows in a closed loop/path through the n and p-type semiconductors to an external load. This pair of n and p-type semiconductors forms a unicouple thermoelectric device. A thermoelectric generator would consist of multiple unicouple thermoelectric devices connected in series, which increases the output voltage, and in parallel to increase the output current. A schematic of TE device has shown below in fig. 1.

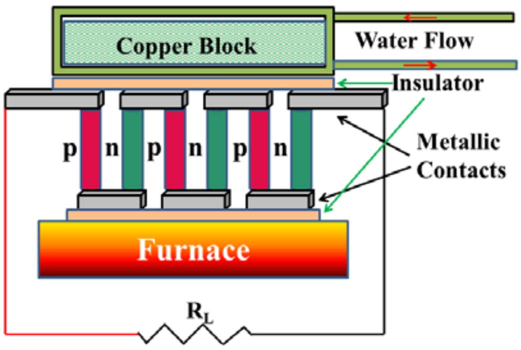

Fig. 1 Schematic View of Thermoelectric Device

4.1 Thermoelectric (TE) Legs:

Thermoelectric device contains n and/or p-type combination of TE materials. The TE device needs to have a compatible n and p-type thermoelectric material. These TE materials can be synthesized through one of the available various synthesizing techniques like spark plasma sintering, arc melting, hot press. Then the synthesized n and p-type TE materials have been cut for measurement of thermoelectric properties. With these optimised TE materials, the desired shape has been cut to make n and p-type thermoelectric couple, known as TE legs. These thermoelectric legs are placed in series through suitable conducting plate as shown in fig. 1.

4.2 Insulating Plate:

Insulating plate separates the metallic contacts of thermoelectric legs from the outer plate of the device, which is conducting in nature to maintain the proper flow of electric current in the circuit. Insulating plates is being used for electrical insulation with high thermal conduction.

High thermal conductivity allows heat transfer at faster rate, whereas electrical insulation prohibits flow of current to outer surface of the device.

4.3 Metal Contacts/Interconnects and Contact Resistance:

In TE devices compatible n and p-type TE legs are connected in series via suitable metallic plates as shown in figure 1. Selection of suitable metallic contact is a major issue; it should be compatible with TE legs. The resistance of interconnects should be as low as possible (say few mΩ). Contact resistance between TE legs & metal plate makes the real difference, so selection of bonding element for making contact between both is real challenge in fabrication of device.

4.4 Cooling System:

In an actual thermoelectric device, it is very difficult to maintain the temperature gradient across the hot and cold ends of the TE legs. Once an end of the device is heated, the magnitude of ΔT gradually decreases and reaches a minimum value. This decrease in the value of temperature difference between the hot and cold ends is due to thermal back diffusion and Joule heating effects. Consequently, the temperature of the cold side increases. Thus, certain strategic improvements and modifications are required for extracting the maximum possible performance of the TE device.

An efficient cooling system is required on the cold plate side to maintain a higher temperature difference across the both ends of the thermoelectric legs. The cooling system consists of a copper block consisting of water inlet and outlet system as shown in the fig. 1.

5. Summary & Conclusions

To overcome the energy crisis, effective ways of energy generation and efficient utilization of available energy resources play avital role. However, conventional energy sources like fossil fuels are now available in very less amount on the earth. Proper management of available energy resources play an important role, because around 50% of generated energy is only utilized & rest of it is being wasted in the form of waste heat. Then, utilization of energy from waste heat is an important task. This waste heat can be properly utilized and converted to electrical energy through thermoelectric devices. Thermoelectric Devices is a solid state device, generates the electrical energy from temperature gradient. TE devices are thermally compatible in the working temperature range. TEGs generates energy for a long period, along with zero emission of greenhouse gases make it more attractive candidate for green energy generation.

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