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Exploration of Thermoelectric Power Generation Possibility from Waste Heat Source using Advanced Thermoelectric Power Generation Simulator

Habib Muhammad Nazir Ahmad[1], Mustafa Mohammad Shaky[2]
[1] Assistant Professor, Department of EEE,Faculty of Engineering, American International University - Bangladesh
[2] Lecturer, Department of Physical Sciences, School of Engineering and Computer Sciences, Independent University, Bangladesh
Corresponding email: showvan@aiub.edu , mustafa.mohammad.shaky@gmail.com

Abstract— This manuscript investigates possibility of using metallic alloy and their performance in terms of efficiency, power generation etc. for generating thermoelectric power from waste heat source. The first part of the manuscript comparatively discusses mainly of different n-type and p-type metallic alloy's conductivity in both electrical and thermal manner and also Seebeck coefficient which is vital parameter for thermoelectric power generation. Later, it's been observed from simulation and plotting of results that BiTeSe_BiSbTe alloy shows maximum efficiency and maximum power can be harvested from this alloy, whereas, SiGe_SiGe alloy shows poor performance in most of the cases.

Index Terms— Thermoelectric, Waste Heat, Metallic Alloy, Seebeck Coefficient, Thermal Conductivity, Electrical Conductivity, ADVTE

1 Introduction

Due to excessive demand to produce electricity, the sources of traditional fossil fuel are shrinking at an alarming rate. Scientists are focusing more on alternative ways to generate energy from easily accessible sources. In our daily life, we use dozens of electronic devices and most of these devices emit or dissipate heat while operating. Since, heat is a form of energy; hence, this waste heat can be converted to another form i.e; electrical energy [1].

One viable solution for generating power or electricity is to harvest heat energy from these devices to generate electricity using Thermoelectric Generator. A thermoelectric generator (TEG) is a device with solid state technology that converts heat into electricity [2] [3]. By using this thermoelectric energy conversion technology waste heat from human body or any kind of heat engines in motorized vehicles, aero planes, ships or power plants can be moderately recovered to generate extra electric power, which will consequently increase energy efficiency [3]. When a TEG is attached directly onto one of these waste heat sources i.e. heat engines, heat from these heat engines flow through the TEG due to the difference in temperature of the engine and the ambient environment. This flow of heat creates a voltage in the TEG by the Seebeck effect, which performs useful work when connected to an external circuit [1] [4]. However, it is an important reminder that the heat dissipation from any kind of heat source largely varies depending on its location and surrounding conditions [1].

Thermoelectric materials allow for direct electricity generation through the Seebeck effect where a temperature gradient applied to a circuit at the junction of two different conductors produces an electromotive force based on the relation $E_{emf}=-S \nabla T$ where S is the Seebeck coefficient (or thermopower) [9]. However the use of thermoelectric modules as solid state heat pumps for heating and cooling applications using the opposite Peltier effect is far more common than their use as solid state generators. Peltier modules, with their ability to heat and cool with great precision, have proved useful in optical equipment, automotive seats, and small consumer refrigerators. Other than fuel-burning generators that utilize thermoelectric technology to produce electricity manufactured by Global Thermoelectric and a few other companies, Seebeck generation products are rather immature [10].

The most common thermoelectric conductors' materials today are alloys of chalcogenides (materials with a chalcogen or IUPAC group 16 anion). Specifically these materials are either based on bismuth telluride (Bi_2Te_3) or lead telluride (PbTe). Bi_2Te_3 can be alloyed with Bi_2Se_3 to form n-type $Bi_2Te_{3-x}Se_x$ and with Sb_2Te_3 to form p-type $Bi_xSb_{2-x}Te_3$. PbTe can be alloyed with PbSe to form p-type $PbTe_{1-x}Se_x$ and with SnTe to form n-type $Pb_{1-x}Sn_xTe$. PbTe has been used successfully by NASA as radioisotope thermoelectric generators (RTGs) but it has not been rejected by all current power generation projects because of the weak mechanical properties during thermal cycling from variable temperature gradient [10].

New material classes could allow for waste heat recovery with better efficiency or use with higher temperature heat sources. These classes include skutterudites, clathrates, Half-Heuslers, and oxides such as cobaltites and perovskites [11]. Other material classes such as silicides [12] and tetrahedrites [13] are primarily considered for their relatively low cost. These new classes have been the subject of a great deal of research but have had limited commercial use due to cost, reliability, efficiency, and processing issues that prevent them being selected over traditional materials [10].

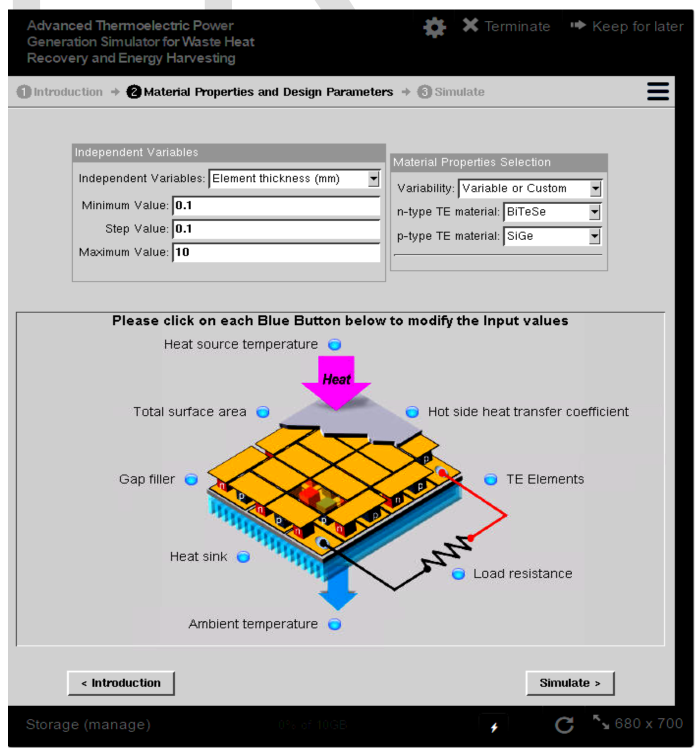
2 Thermoelectric Waste Heat Recovery

The lack of moving parts in thermoelectric generators (TEGs) holds the promise of reduced O&M costs and longer time between failures. These potential benefits make thermoelectric generators important to consider for industrial waste heat recovery applications. Large scale TEGs (greater than 1 kW) that generate general purpose power (i.e. power not meant for a particular dedicated application) from industrial waste heat, are not in general use at the time of this report. The largest commercially available TEG systems are remote generators manufactured by Global Thermoelectric, a Calgary based company recently acquired by Gentherm, which has installed over 20,000 TEGs. These systems are generally fuel burning with a maximum power around 500 W, and they provide electricity along gas pipelines and on offshore oil platforms, among other similar locations [14]. However, there are a few larger waste heat systems that have been installed and discussed in literature. An extensive study of a thermoelectric generator in a working glass plant [15] discussed the difficulty of delivering heat from the exhaust stream to the generator via a heat pipe. The power generation in this study was not cost effective, and the researchers faced great difficulties with degradation of heat flux through the heat pipe due to corrosion in the exhaust flue. The iron and steel industry is a common target for waste heat recovery technology based on its high quality waste heat. As such, the iron and steel industry has seen some of the most extensive discussion of industrial thermoelectric waste heat applications in literature. One notable study involved a TEG with 16 bismuth telluride modules placed above an afterburner flame in the exhaust system of a carburizing furnace at a Komatsu steel plant in Awazu [16]. The afterburner flame was estimated to produce up to 20 kW of heat and to induce temperatures between 120 and 250 °C on the heat collection place of the water cooled TEG. The modules used were developed by a Komatsu subsidiary, had a potential power density of 1 W/cm², and the highest conversion efficiency of any commercial TE module when they were announced in 2009 [17]. The modules were very expensive, however, with a price of roughly $30/W when they were released. A later study at this plant has demonstrated power outputs on the order of 240 W for single generators, and discussed the installation of power hardware to effectively manage the output of multiple generators [18].

Furthermore, there has been an explosion in the growth of use of wearable electronics and sensors in the recent years and since with every breakthrough there are some drawbacks, these new devices are still powered by batteries and require constant recharging and replacement [1] [5] [6], which is why, interest in synthesizing flexible thermoelectric materials, organic and inorganic, with scalable approaches for wearable energy harvesting applications has also boosted up [1]. But, the large-scale use of this conversion technology is currently limited by its efficiency and cost of the materials [7]. Therefore, it is very important to identify which material gives better power output or efficiency and in our paper, we tried to put out a summary on the effectiveness of different types of inorganic materials against a wide range temperature and their thickness. In order to find out the responses of different kinds of materials against temperature and their thickness ADVTE (Advanced Thermoelectric Power Generation Simulator) tool was used.

3 ADVTE Simulation tool

ADVTE tool allows us to perform realistic power generation performance simulations of a multi-element thermoelectric module for waste heat recovery energy harvesting applications. Unlike many other thermoelectric (TE) simulation tools, ADVTE can simulate with temperature-dependent material properties, i.e. Seebeck coefficient, electrical conductivity, thermal conductivity as a function of temperature, for accurate TE performance prediction. Several important materials such as BiTe alloys, MgSnSi, and SiGe are included in the built-in database in the tool [24]. By using this tool, we can select TE material properties or change the maximum, minimum and vary step sizes of independent variables i.e. element thickness, element area or load resistance of our own choice. We are also allowed to modify the input values of heat source temperature, total surface area, ambient temperature, gap filler, heat sink, hot side heat transfer coefficient etc. and observe the changes in outputs. For our simulation, we used the default values of input and independent variables, but changed the material properties. Screenshot of a randomly selected TE alloy combination is shown below as Fig.1 (a) (b).



1 (a)

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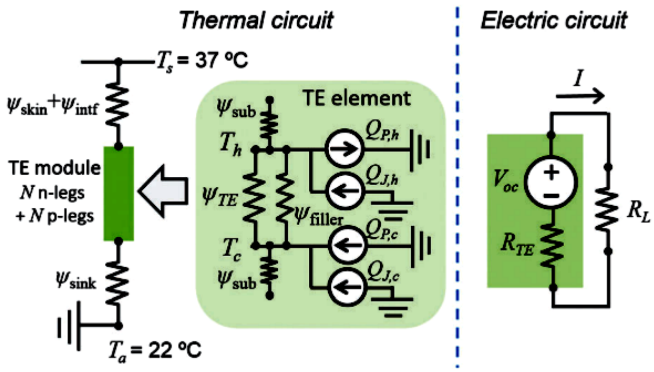


1 (b)

Figure 1: (a) ADVTE Simulation Tool, (b) the thermal and electric circuit models used for device performance simulation

4 SIMULATED WAVE SHAPES

In this paper, we have observed the responses of nine combinations of different alloys such as BiTeSe, MgSnSi, SiGe, BiSbTe and PbTe with respect to a wide a range of temperature (300K-800K) such as N-Type Electrical Conductivity (1/Ohm-cm), N-Type Seebeck Coefficient (µV/K), N-Type Thermal Conductivity (W/mK), P-Type Electrical Conductivity (1/Ohm-cm), P-Type Seebeck Coefficient (µV/K) and P-Type Thermal Conductivity (W/mK) of the observed alloys. The same combination of alloys are also used to observe their responses with respect to thickness (0.1 mm-10 mm) in order to observe such as Efficiency (%), Power Output (W), Resulting Current (A) and Voltage Across Load (V). The combinations of these alloys are BiTeSe__BiSbTe, BiTeSe__PbTe, BiTeSe__SiGe, MgSnSi__BiSbTe, MgSnSi__PbTe, MgSnSi__SiGe, SiGe__BiSbTe, SiGe__PbTe, SiGe__SiGe.

From Fig. 2 to 7, the values of N-Type Electrical Conductivity (1/Ohm-cm), N-Type Seebeck Coefficient (µV/K), N-Type Thermal Conductivity (W/mK), P-Type Electrical Conductivity (1/Ohm-cm), P-Type Seebeck Coefficient (µV/K) and P-Type Thermal Conductivity (W/mK) are placed on Y-axis respectively and values of temperature (K) are placed on X-axis. From Fig. 8 to 11, the values of Efficiency (%), Power Output (W), Resulting Current (A) and Voltage Across Load (V) are placed on Y-axis respectively and values of thickness (mm) are placed on X-axis.

Electrical conductivity is the degree of a material's (n-type or p-type) capability to allow the transport of an electric charge and calculated as the ratio of the current density in the material to that electric field that causes the flow of current [28].

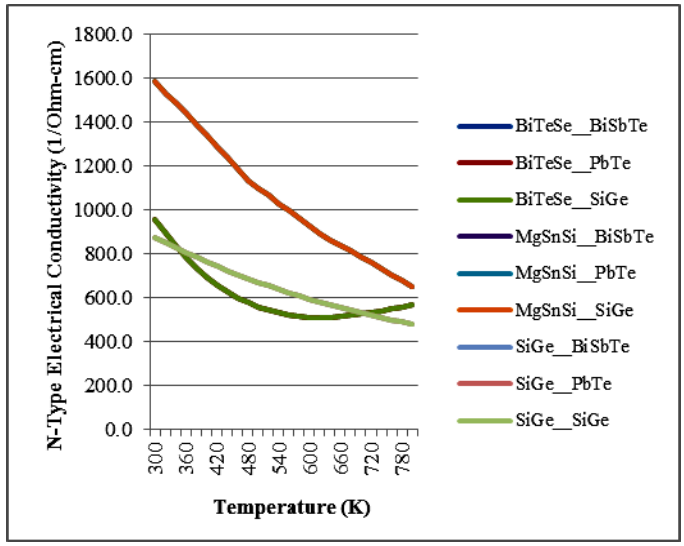
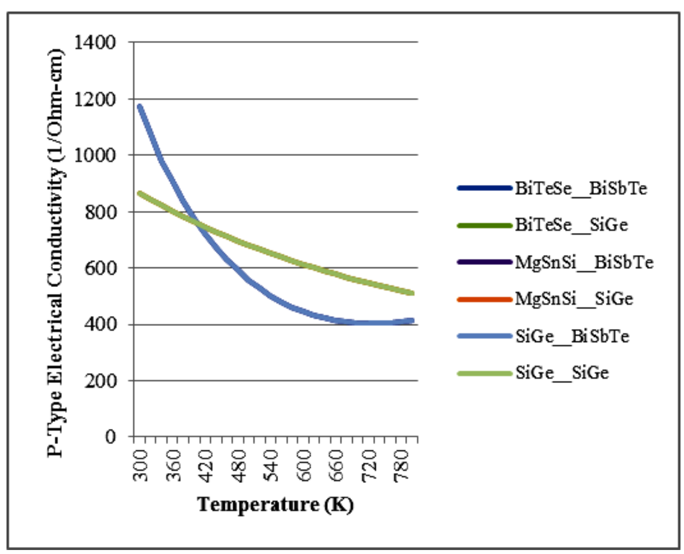


Figure 2: Temperature vs. N-Type Electrical Conductivity (1/Ohm-cm)

In Fig. 2 we can see that MgSnSi__BiSbTe, MgSnSi__PbTe and MgSnSi__SiGe alloys are in dominating position all the way from 300 K to 800 K and have maximum N-Type Electrical Conductivity. On the other hand, BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe are leading SiGe__BiSbTe, SiGe__PbTe and SiGe__SiGe from 300 k to 340 K. But, from 360 K to 700 K, SiGe__BiSbTe, SiGe__PbTe and SiGe__SiGe are showing better outputs than BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe and after 700 K to 800 K it's just the opposite. So, by considering their responses against temperature, MgSnSi__BiSbTe, MgSnSi__PbTe and MgSnSi__SiGe have maximum N-Type Electrical Conductivity and BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe have minimum (most of the cases) N-Type Electrical Conductivity.



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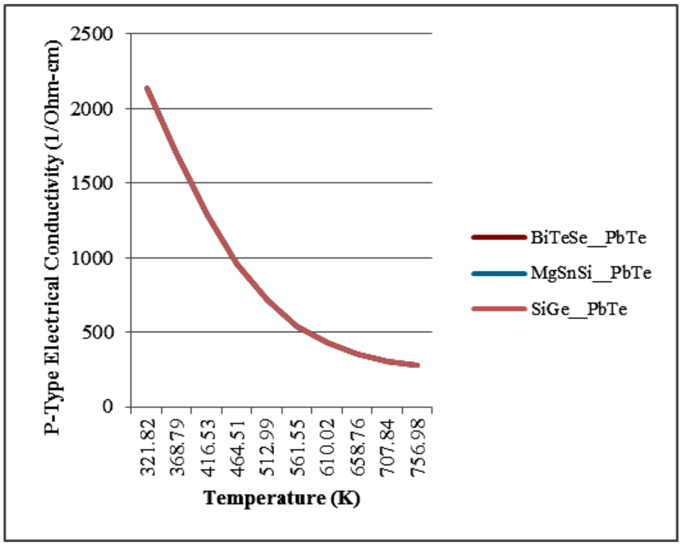


3 (b)

Figure 3 (a) (b): Temperature vs. P-Type Electrical Conductivity (1/Ohm-cm)

Among the Fig. 3 (a) and (b), we can see from Fig. 3 (b) that BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys are showing maximum responses from 300 K to 520 K. After that, in Fig. 3 (a) BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe are showing high yield up to 800 K. But, after showing a better output than BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys from 300 K to 400 K, the BiTeSe__BiSbTe, MgSnSi__BiSbTe and SiGe__BiSbTe have minimum outputs compared to BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys. Therefore, by considering the maximum conductivity reached, BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys have maximum and BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys have minimum P-Type Electrical Conductivity.

Electrons are considered to be the carriers of both heat and electricity. An opposing electric field is created due to a net diffusion of electrons from the hot end toward the cold end of an electrically conductive wire with the existence of a temperature gradient. Seebeck Coefficient (also known as thermopower [27], thermoelectric power and thermoelectric sensitivity [26]) is a material property which determines the performance of thermocouples and defined as Seebeck Voltage per unit temperature [8] or measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material, as induced by the Seebeck effect [25]. Although, the SI unit of the Seebeck Co-efficient is Volts per Kelvin (V/K) [25], it is more often given in microvolts per kelvin (μV/K). If the temperature difference, ΔT between two material is insignificant, then the Seebeck coefficient can be expressed as,

$$S= - \Delta V/\Delta T \text{ or } - (V_{left} - V_{right}) / (T_{left} - T_{right}) \ [26].$$

The Seebeck effect, which tends to push charge carriers towards the cold side of the material until a compensating voltage has built up, is generally controlled by the contribution from charge carrier diffusion. Therefore, in p-type semiconductors, armed with holes mostly, S is positive and n-type semiconductors, armed with electrons mostly, S is negative. However, in most conductors, the charge carriers exhibit both electron-like and hole-like performance and the sign of S usually depend on which of them predominates [26].

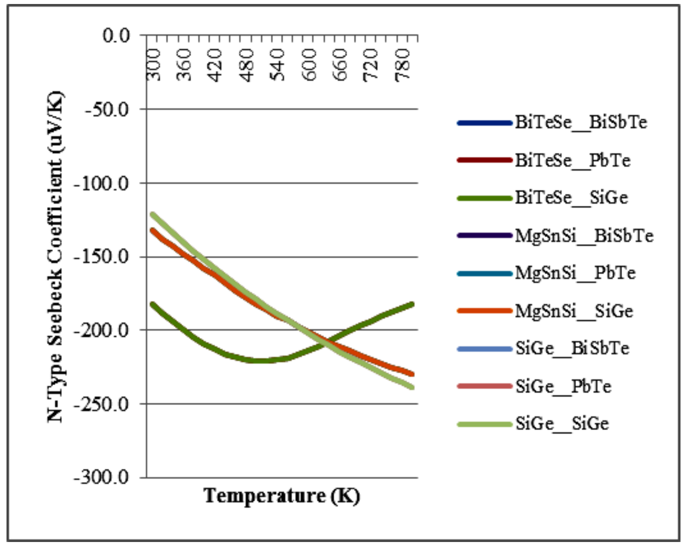
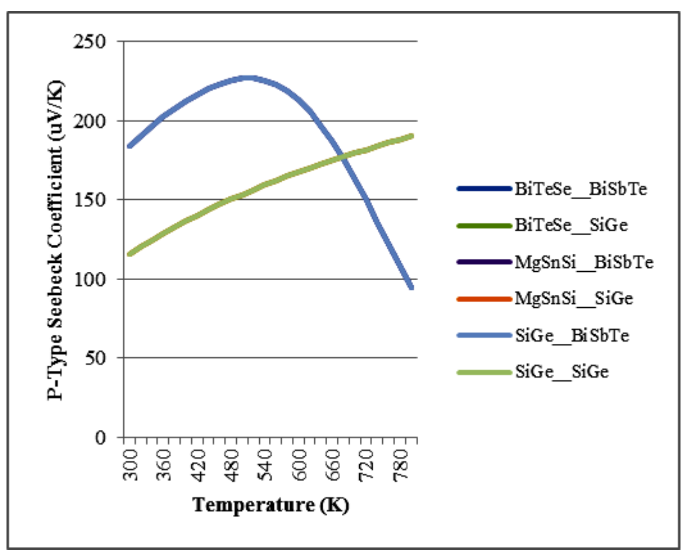


Figure 4: Temperature vs. N-Type Seebeck Coefficient (μV/K)

In Fig. 4 we can see that BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe are showing maximum outputs from 300 K to 620 K. But, after that SiGe__BiSbTe, SiGe__PbTe and SiGe__SiGe alloys are leading the way; however, the same set of alloys is showing minimum output from 300 K to 540 K. Moreover, from 560 K to 800 K MgSnSi__BiSbTe, MgSnSi__PbTe and MgSnSi__SiGe alloys are showing minimum outputs. Therefore, BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe alloys have minimum and SiGe__BiSbTe, SiGe__PbTe and SiGe__SiGe alloys have maximum N-Type Seebeck Coefficient.



5 (a)

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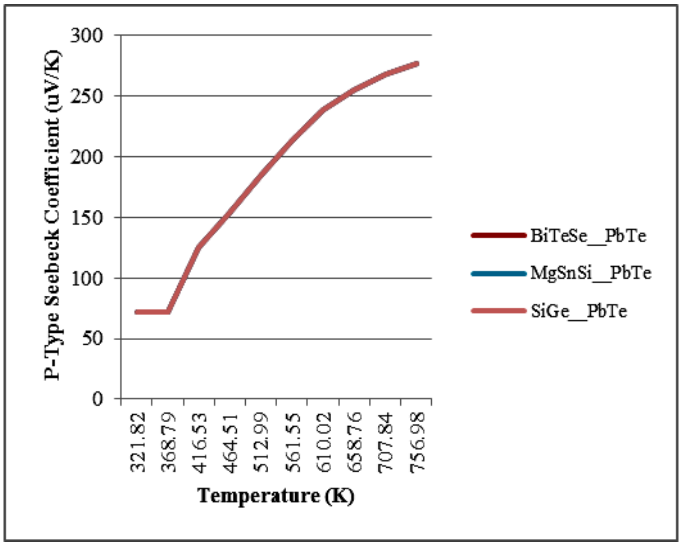


5 (b)

Figure 5 (a) (b): Temperature vs. P-Type Seebeck Coefficient (µV/K)

In Fig. 5 (b) we can see that at first BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys have constant output, which is minimum among all of the alloys of figure5 (a) and (b). But, as the temperature increases, it is clear that the outputs of these alloys are showing maximum output. However, in figure 5 (a) BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys are showing minimum responses from 300 K to 660 K, but before that it is leading over BiTeSe__BiSbTe, MgSnSi__BiSbTe and SiGe__BiSbTe. That means, if we consider the maximum value reached, BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys have maximum and BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys have minimum P-Type Seebeck Coefficient. Thermal Conductivity is defined as the rate at which heat, with a temperature gradient of one degree per unit distance, passes per unit time through a unit area of definite material [29] [30].

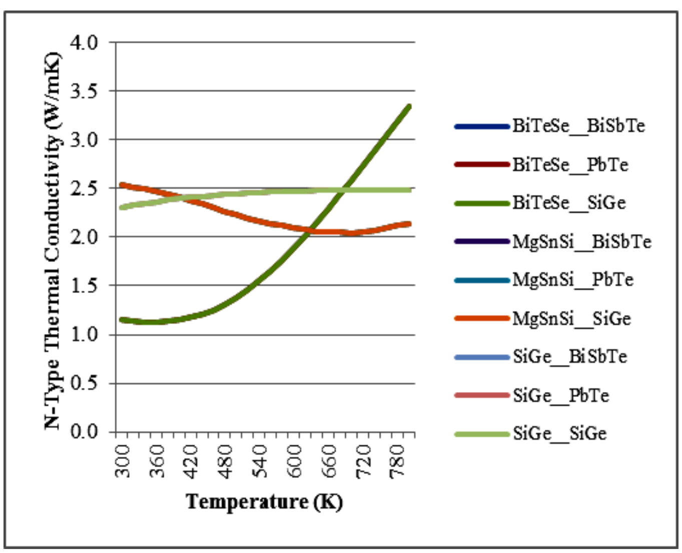
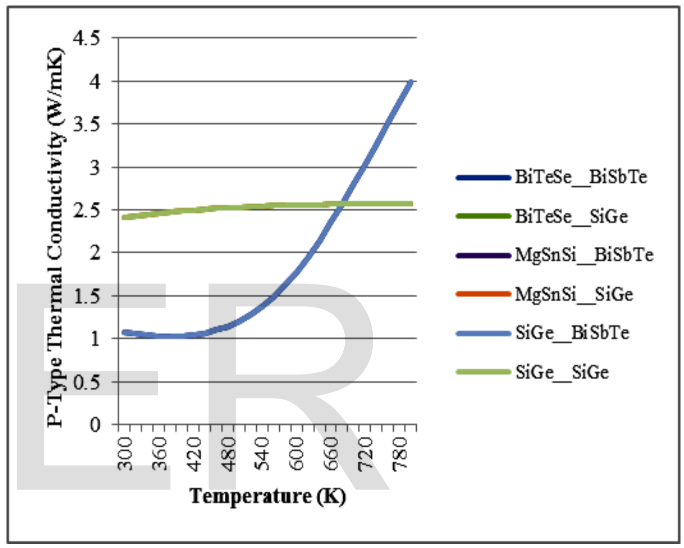
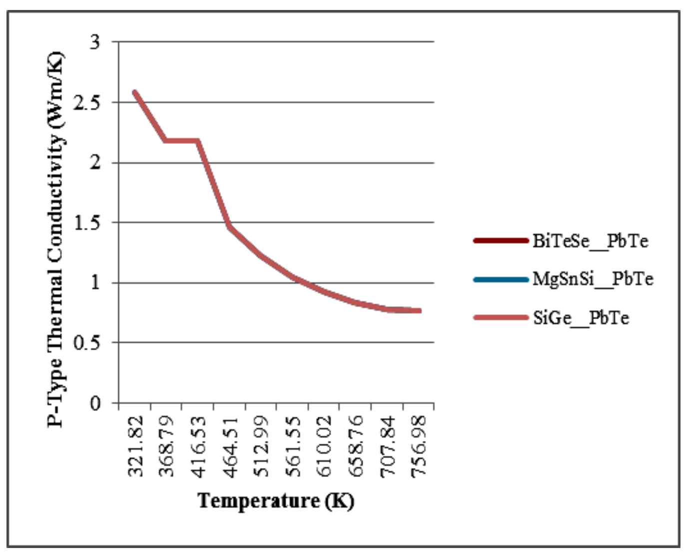


Figure 6: Temperature vs. N-Type Thermal Conductivity (W/mK)

In Fig. 6 we can see that although are showing maximum responses from 300 K to 360 K, but later as they intersects the response curves of SiGe__BiSbTe, SiGe__PbTe and SiGe__SiGe alloys at 380 K, they are showing minimum outputs compared to MgSnSi__BiSbTe, MgSnSi__PbTe and MgSnSi__SiGe alloys. But, when MgSnSi__BiSbTe, MgSnSi__PbTe and MgSnSi__SiGe alloys intersects the responses of BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe alloys show minimum responses and after 700 K the same alloys have maximum N-Type Thermal Conductivity. Therefore, BiTeSe__BiSbTe, BiTeSe__PbTe and BiTeSe__SiGe alloys have maximum N-Type Thermal Conductivity and MgSnSi__BiSbTe, MgSnSi__PbTe and MgSnSi__SiGe alloys have minimum N-Type Thermal Conductivity.



7(a)



7(b)

Figure 7 (a) (b): Temperature vs. P-Type Thermal Conductivity (W/mK)

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Between Fig. 7 (a) and (b), in Fig. 7 (b) we can observe that for a moment BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys have maximum response, but after that the response has gone done slowly. On the other hand, in Fig. 7 (a), BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys are showing almost steady response throughout the whole temperature range. However, BiTeSe__BiSbTe, MgSnSi__BiSbTe and SiGe__BiSbTe alloys have minimum output from 300 K to 660 K. But, after, when the response curves of BiTeSe__BiSbTe, MgSnSi__BiSbTe and SiGe__BiSbTe alloys intersect the responses of BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe alloys at 680 K, the BiTeSe__BiSbTe, MgSnSi__BiSbTe and SiGe__BiSbTe have maximum P-Type Thermal Conductivity and BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys have minimum P-Type Thermal Conductivity.

So, based on their maximum output achieved, we can conclude that BiTeSe__BiSbTe, MgSnSi__BiSbTe and SiGe__BiSbTe have maximum P-Type Thermal Conductivity and BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe alloys have minimum P-Type Thermal Conductivity.

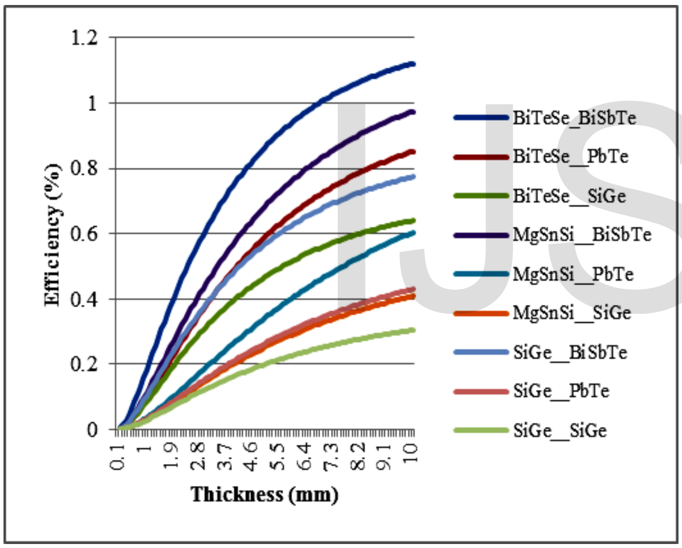

Figure 8: Thickness (mm) vs. Efficiency (%)

In Fig. 8, the BiTeSe__BiSbTe shows the best efficiency, which has a maximum efficiency of 1.1% and SiGe__SiGe shows the least efficiency, which is 0.3%, among all of them with increasing value of thickness.

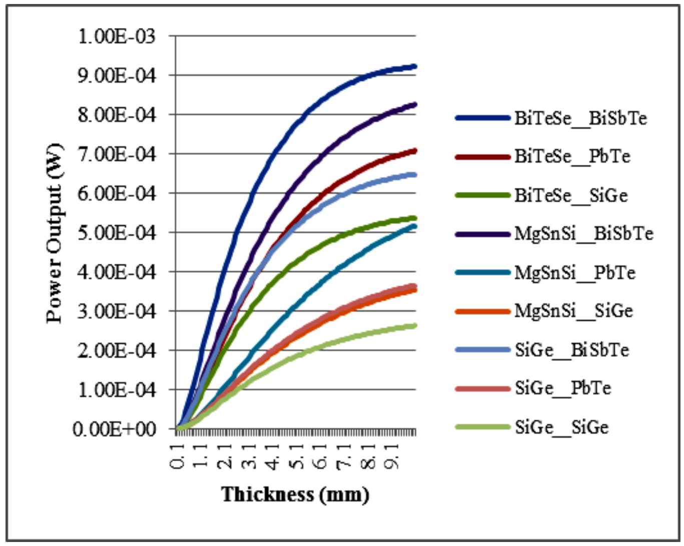

Figure 9: Thickness (mm) vs. Power Output (W)

In Fig. 9, SiGe__SiGe shows the least power generation, which is 2.63×10^{-4} W against the alloy thickness of 10 mm and BiTeSe__BiSbTe alloy shows the highest power generation with increasing thickness. It has shown 9.23×10^{-4} W against the same alloy thickness. Since, the main purpose of TEG is to generate electrical power, hence, the more the generated power the better the performance.

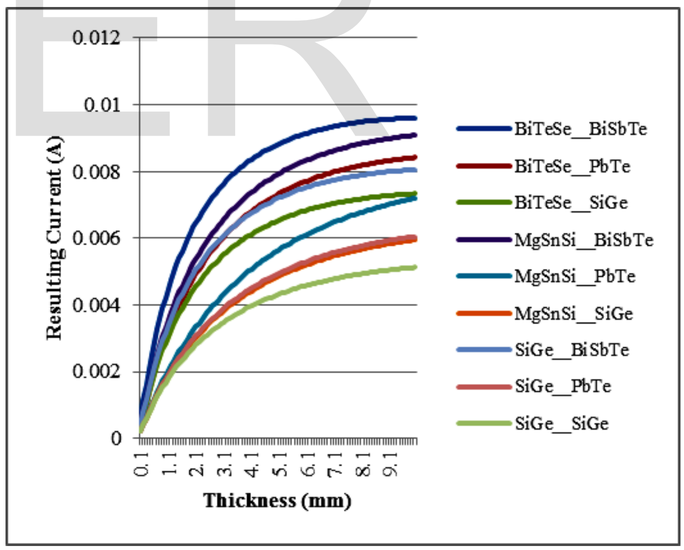

Figure 10: Thickness (mm) vs. Resulting Current (A)

In Fig. 10, BiTeSe__BiSbTe alloy results best output current of 9.61×10^{-3} A and SiGe__SiGe results least output current of 5.13×10^{-3} A against the maximum alloy thickness of 10 mm.

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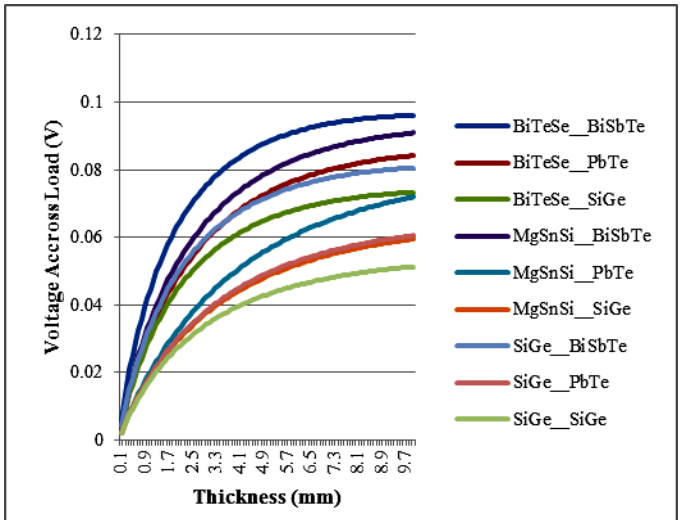

Figure 11: Thickness (mm) vs. Voltage Across Load (V)

In Fig. 11, BiTeSe__BiSbTe has highest amount of voltage across the load, which is 9.61×10^{-2} V and SiGe__SiGe has lowest amount of voltage across the load, which is 5.13×10^{-2} V against 10 mm alloy thickness.

Thus, we can evidently conclude that in terms of maximum efficiency, power generation, output current and voltage across the load, the BiTeSe__BiSbTe alloy is showing superior responses over SiGe__SiGe alloy.

5 Summary

Table I: Maximum and Minimum Response observed with respect to the Device Parameters

Device Parameter	Maximum Response Observed	Minimum Response Observed
N-Type Electrical Conductivity (1/Ohm-cm)	MgSnSi__BiSbTe, MgSnSi__PbTe, MgSnSi__SiGe	BiTeSe__BiSbTe, BiTeSe__PbTe, BiTeSe__SiGe
P-Type Electrical Conductivity (1/Ohm-cm)	BiTeSe__PbTe, MgSnSi__PbTe, SiGe__PbTe	BiTeSe__SiGe MgSnSi__SiGe, SiGe__SiGe
N-Type Seebeck Coefficient (μV/K)	SiGe__BiSbTe, SiGe__PbTe, SiGe__SiGe	BiTeSe__BiSbTe, BiTeSe__PbTe, BiTeSe__SiGe
P-Type Seebeck Coefficient (μV/K)	BiTeSe__PbTe, MgSnSi__PbTe and SiGe__PbTe	BiTeSe__SiGe MgSnSi__SiGe and SiGe__SiGe
N-Type Thermal Conductivity (W/mK)	BiTeSe__BiSbTe, BiTeSe__PbTe, BiTeSe__SiGe	MgSnSi__BiSbTe, MgSnSi__PbTe, MgSnSi__SiGe
P-Type Thermal Conductivity (W/mK)	BiTeSe__BiSbTe, MgSnSi__BiSbTe, SiGe__BiSbTe	BiTeSe__PbTe, MgSnSi__PbTe, SiGe__PbTe
Efficiency (%)	BiTeSe__BiSbTe	SiGe__SiGe
Power Output (W)	BiTeSe__BiSbTe	SiGe__SiGe
Resulting Current (A)	BiTeSe__BiSbTe	SiGe__SiGe
Voltage Across Load (V)	BiTeSe__BiSbTe	SiGe__SiGe

6 Potential Benefits

To obtain an estimate of the amounts of waste heat in each industrial sector, the AMO's Manufacturing Energy and Carbon Footprints data [19] were used. An initial estimate of the potential of thermoelectric energy harvesting from the waste heat of manufacturing plants can be obtained by choosing some fraction of the heat that can be recovered by generation systems, and then estimating an efficiency value for those systems. The choice for the low end of the recoverable heat range was 10% based on an estimate from [15], and the high end of 25% was based on heat recovery calculations for boiler exhaust from [20].

Manufacturing Sector	Process Heating Energy Use (TBtu)	Process Heating Energy Loss (TBtu)	Recoverable Heat (Min–Max) (TBtu)	TE Potential (Min–Max) (GWh)
Petroleum Refining	2,250	397	40–99	582–1,454
Chemicals	1,455	328	33–82	481–1,201
Forest Products	980	701	70–175	1,027–2,567
Iron and Steel	729	334	33–84	489–1,223
Food and Beverage	518	293	29–73	429–1,073
Cement	213	84	8–21	123–308
Glass	161	88	9–22	129–322
Fabricated Metals	139	49	5–12	72–179
Transportation Equipment	65	23	2–6	34–84
Foundries	61	28	3–7	41–103
Plastics and Rubber	88	20	2–5	29–73
Textiles	40	23	2–6	34–84
Alumina and Aluminum	81	37	4–9	54–136
Computers, Electronics & Electrical Equipment	42	15	2–4	22–55
Machinery	37	13	1–3	19–48
All Manufacturing	7,204	2,567	447–1,117	6,547–16,368

Figure 12: Thermoelectric generation potential estimate by major industrial sectors based on (Energetics Incorporated, 2014)

The results for such an estimate can be seen in Fig. 12 with the recoverable heat as a range from 10% to 25% of the sector's process heating losses and the thermoelectric generation efficiency assumed to be 5%. Five percent is a fairly typical efficiency value given current thermoelectric technology. The thermoelectric recovery potential for all of US manufacturing in this estimate is 6.5–16.4 TWh of electrical energy for 2010 which is 0.9–2.3% of the 712 TWh of on-site electrical energy used in US manufacturing plants that year. This is 1.5–3.7% of the 433 TWh of waste heat predicted for the 2,473 TWh worth of annual industrial energy consumption in BCS Incorporated's report for the DOE's Industrial Technology Program [21].

7 Conclusion

More research is needed into heat transfer in thermoelectric generators. This includes cost optimization of heat exchangers that collect source heat and transfer heat to cooling water, but it also would include heat transfer within the module.
Costs for electrically insulating plates (usually ceramic) must be reduced while maintaining good thermal conductivity. Electrical interconnects and other interfaces must be engineered to maximize device reliability and thermal conductivity.

Using more corrosion resistant heat exchangers would allow thermoelectric heat recovery from a more diverse range of industrial exhaust streams. Studies, to co-optimize the thermal and electrical properties of the whole TEG system while maintaining its mechanical integrity, are also important [22].

Thermoelectric generation could be found ineffective if TEGs never reach a low enough price point for wide adoption. A frequently discussed cost target for thermoelectric generation is $1/W which, given a fairly conservative set of assumptions discussed earlier, would lead to electricity costs competitive with the average cost of electricity for US industrial use in 2013: 6.82 C/kWh [23]. Thermoelectric generators might also be found to degrade when exposed to variable temperature environments over multi-year lifespans. Other countries could also have advantages in thermoelectric production due to their extant research base (Japan) or manufacturing infrastructure (China, Vietnam). Other technologies for waste heat recovery like low temperature Rankine cycle variants, load preheating, or exotic solutions like phase change material generators could see breakthroughs that would cause them to outcompete TEGs. Preheating and Rankine cycle variations are more commercially established than TEGs as industrial waste heat recovery solutions, but thermoelectrics have advantages of minimal maintenance requirements, as well as option to install with minimal downtime and minimal effects to existing systems. Finally, if higher efficiency industrial processes are adopted or value chains change to lower waste heat options (integrated steel mills to mini-mills for example) then the amount for waste heat available for thermoelectric recovery would decrease, leading to less of a return on thermoelectric R&D investment.

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