Review of Potential Thermoelectric Energy Harvesting using Seebeck Effect

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***Abstract*— Now a days, the world tend to use renewable energy such as wind, solar, and biomass energy to dispensing on fossil fuel and saved other type of energy like electricity. Thermoelectric based on Seebeck effect an important technique that used as a renewable energy to produce electricity by harvesting waste heat from applications that produce thermal energy as a result of its operation. This study presented review of thermoelectric which based on Seebeck effect with its historical, cost, and applications in engine and human body. This review show that the thermoelectric application could be classified based on average power which generated as low power generation (human applications) and high power generation (internal combustion engine applications). The review show that the voltage generated from thermoelectric generator as a result of heat harvesting from engine application is more than that generated as a result of heat harvesting from human body application.**

Keywords—Seebeck; Peltier; Thermoelectric; Energy Harvesting;

I. INTRODUCTION

Green technologies like wind, solar, hydrogenation and biomass energy are develop to solve energy problems. Further, new energy from different surrounding energy sources such as vibration, heat and noise can be changed over into electrical energy. Energy harvesting one of the most important type of green technologies which increased attention to reducing dependence on fossil fuel [1], [2]. The present researcher moving towards new technologies like thermoelectric technology to convert thermal energy into electrical energy [3]. Thermoelectric (TE) mention a relationship between electrical and thermal phenomena and defined as a technology and science related to the cooling and power generation by using Peltier and Seebeck effects respectively, in other words, it is solid-state that convert thermal energy directly to electricity or electric power to cooling or heating power [4]. By increasing requirement for clean energy sources, the clean energy from the thermoelectric phenomenon is the truth worthy of research and study [5]. Other things that should be considered in green technology is the energy cost. Energy cost is a very critical point in many applications, therefore, using thermoelectric devices are the best option for power generation source [6]. Both of generating and refrigerating process can be used by thermoelectric devices (TE). Thermoelectric generator (TEG) is generating power depending on Seebeck effect, while thermoelectric coolers (TECs) or thermoelectric modules (TEMs) are depending on Peltier effect [7], [8]. In spite of thermoelectric has been known before 190 years, there are still not spreads well application in the world due to low efficiencies of commercial modules [1]. Both two types of thermoelectric have an endless shelf life, highly reliable, environmentally friendly, scalable, no mechanical parts, silent in operation, small size and light in weight, as well as, it is required much less maintenance comparing with other devices [1], [9], [10]. This study presented thermoelectric review and classified according to its development, application in engine and human body, and economic in order to easy search and study.

II. THERMOELECTRIC MODEL DESCRIPTION

Basically, a thermoelectric module which is using in the electricity generation has a thermo element. The thermo element involve from Bismuth telluride (Be_2Te_3) material which is one of the commercial semiconductors that used in thermoelectric device. There are two semiconductors (n-type and p-type) which connected in series and parallel, current and heat flow in the same direction through (n-type) semiconductor, and heat flow in opposite directions of current flow in (p-type) (see fig. 1) [11], [12]. Consequently, a large number of thermo elements are electrically connected in series in order to increase the operating voltage and thermally connected parallel in order to increase the thermal conductivity. All this arrangement are fixed between two ceramic plates covered cold and hot sides [3], [7], [13], [14]. In thermoelectric module the voltage in open circuit is proportional with temperature gradient. Thermoelectric efficiency can be expressed as the rate between electrical powers P to heat transfer Q across thermoelectric.

$$\eta = \frac{P}{Q} \tag{1}$$

The conduction heat transfer can be expressed as [15]–[17].

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$$Q = -kA\frac{\Delta T}{\Delta X} \quad (2)$$

$$\Delta T = T_{h-}T_c \quad (3)$$

Where:

η: Thermoelectric efficiency %
P: Thermoelectric power (W)
Q: Heat transfer through thermoelectric
k: Thermal conductivity
A: Heat transfer surface area
ΔX: Thermoelectric thickness

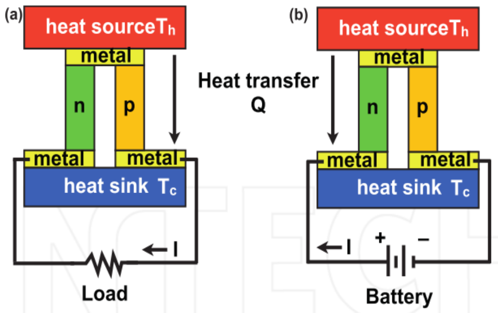

Fig.1. (a) Thermoelectric generator TEG. (b) Thermoelectric cooler TEC [18].

III. THERMOELECTRIC DEVELOPMENT

In 1821, Thomas Seebeck noticed that a circuit made from two dissimilar metals at different temperature with junctions would deflect a compass magnet [8], [19]. In 1822 and 1823 Thomas Seebeck discovered voltage generated at the junction conductors or semiconductors when the junctions subjected to a temperature gradient [5].

$$\alpha = \frac{V}{\Delta T} \quad (4)$$

Where:

α: Seebeck coefficient
V: Voltage

Peltier discovered in 1834 that producing heating or cooling when electrical current flow through two junctions of dissimilar metals after that Lenz found in 1838 that heating or cooling process depending on current flow direction through the metals [20].

$$\pi = \frac{I}{q} \quad (5)$$

Where:

π: Peltier coefficient
I: Current
q: Heat flow rate

Lord Kelvin (William Thomson) in (1855) found that the Seebeck and Peltier effects are different appearance of one effect and present the relationship between the Seebeck coefficient α and Peltier coefficient π as equation (6) [21] [22]. After that many research have been interested like Christophe Goupil presented thermodynamics of thermoelectricity [14]. D.M.Rowe present an environmentally friendly that generated power [23]. Snyder explained complex thermoelectric materials in thermoelectric technology [19].

$$\pi_{AB} = \alpha_{AB}\,.T \quad (6)$$

D.M. Rowe (1995) explain that because limitation of temperature gradient, the application were still not progressing rapidly until 1930s when semiconductors have been discovered [24].

IV. THERMOELECTRIC APPLICATIONS

Thermoelectric applications have been seen in a wide areas such as industrial, avionics, military, medical, telecommunic-ations laboratory and scientific field [4]. However, widely thermoelectric devices obtainable have low efficiency by around 5-10% comparing with other technologies. Thermoelectric device is controlled by the several parameters such as, the figure of meritZ_T, cross sectional area and length of thermoelectric elements, hot and cold end temperatures, contact resistance and load resistance. All this parameters or factors explain the guidelines to boost thermoelectric efficiency in the future studies [10], [25], [26].

1) Engine Applications

Liang depended on exhaust gas with low temperature (TEG) Be_2Te_3 one and two stage, he proved that when the temperature under 800 K and single stage TEG the performance is better than one two stage TEG while the performance of two-stage is better than one stage TEG at hot source is higher than 800 K [27].

S.R.Jumade presented a survey on thermoelectric technology when using in internal combustion engine in order to recover waste heat energy and demonstrates thermoelectric material, compared and evolution between many thermoelectric generators [28].

Crane got 40 W/L as net power densities when he used $Be_2\,Te_3$ thermoelectric from heat exchangers. His modules depended on the waste heat in air cooling [29].

According to Chien Chang Wang designed thermoelectric devices converted environmentally friendly energy in an air cooling with two stage heat sink, the output power thermoelectric generator density is advanced by 88.7% and the heat sink efficiency has been decreased about 20.93% according to normal case. The author recommended that the optimum result of power density when the frontal area of the heat sink increase and length of the heat sink decrease [30].

According to Hsiao the maximum power, current and maximum power density is 0.43W, 0.35A, and 51.13mWcm^{-2} respectively are generated from the module which arranged on IC engine. At temperature different 290˚C, the maximum power has been produced. The performance of the module on the exhaust pipe higher than the performance on the radiator in the same module [31].

In Brazil, year 2011 the number of cars was 39,832,919 at the same month in 2012 the total of cars was 42,682,111. This obviously during one year the percentage increase about 7.15%. The expected number of cars will be reach to 4,272,478 toe/year. So it is expected to increase the emission of carbon and air pollution. As in common, the theoretical output of combustion engine about 33%. Brazilian have been examined how much could be utilized from energy

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source if the thermoelectric modules has been used in airplane, ceramics industry and new cars. Especially from combustion engine when using thermoelectric module the power is a friendly environment, clean and no emission of carbon. Furthermore The amount of saving or utilization about 8.64 % [32].

Yuchao Wang used exhaust gas as heat source of TEG and presented that when internal resistance is lower than external resistance the efficiency and maximum power of TEG become clear [33].

N.D.Love show that decreasing in module efficiency between 0.95% to 0.6% and increase in overall module output power between 2 to 3.8 [34].

A. *Human Applications*

From human body heat TE shirt has been fabricate in order to generate power at ambient temperature 15˚C the power has been generated is 5 mW and 0.5 mW at ambient temperature 27˚C. After 9 months of using this shirt produced more energy if it has worn about 10 h/day. TE shirt is made from cotton layer so it is comfortable to human skin. This power suitable for low supplying power which use for example health monitoring devices [35].

At a temperature gradient is 15 K the power has been generated by dispenser printing technique from human body is 224 nW, 15.8μA and 14.2mV when TEG applied on the human body. The TEG was designed based on Seebeck effect therefore the power which generated proportional with temperature gradient, in this module of TEG the hot side is human body and cold side was ambient temperature. TEG could be able to generate more than 146.8nW when the ambient temperature is 5˚C [36].

Yong Du fabricated TEG device which produced output voltage of 4.3mW when temperature gradient is 75.2 K to harvest energy from human body [37].

The voltage which generated between 120 mV to 240 mV and maximum current reach to 18 mA at temperature gradient 3K to 6K when the cold side was ambient temperature and hot side was human body [38].

Marianne Lossec study the best size of TEG with and without using heat sink when TE generate electrical power from human body [39].

V. COST CONSIDERATIONS

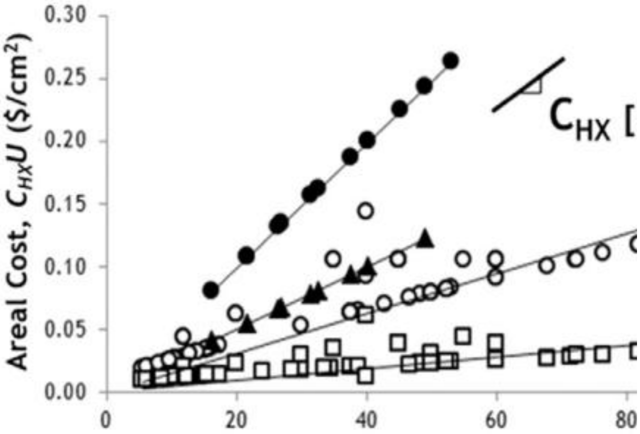
The manufacture cost of TE material and device is extremely depend on its manufacture technology and marketing. As a result of expansion of TE materials, the cost of TEG will be lower costs. The material composition have strong effect on the TE material cost. Regarding to material, the material cost of some TE types are shown in table (1) [40].

Leblanc Proved that the cost of thermoelectric is directly proportional with heat transfer coefficient U (mW/cm^2.K), as shown in fig. (2). In some application the bulk TE material cost of approximately 1$/W when the temperature up to 275˚C of thermoelectric material [40].

Bed Poudel developed nanostructure synthesis procedure which has low cost method, so this technique developed the performance of TEG [41].

According to Cronin B. Vining about 13US$ million has been shared from US Department of Energy to support and develop thermoelectric technology [42].

D.M.Rowe in 1999 explained that the cost is not major consideration in special application such as medical, military and space application [24].



Exchanger Heat Transfer Coefficient, U ($M_w/cm^2.K$)

Fig. 2. The cost of heat exchangers related to overall heat transfer coefficient, or U-value [43]. The slope is the heat exchanger cost per thermal conductance. The figure is reproduced from [44].

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Table (1) Material identification table

Material type	ID	Material name	Manufacturing type	Material cost ($/Kg)
Chalcogenides and SiGe	1	$Bi_2 Te_3$	Bulk	110
	2	$Bi_{0.52}Sb_{1.48}Te_3$	Bulk	125
	3	$Bi_{0.52}Sb_{1.48}Te_3$	Nanobulk	125
	4	$Bi_{0.54}Te_{0.46}$	Nanowire	84
	5	$(Na_{0.0283}Pb_{0.945}Te_{0.9733})$ $(Ag_{1.11}Te_{0.555})$	Nanobulk	81
	6	Bi-doped Pb$Se_{0.98}Te_{0.02}/PbTe$	superlattice	55
	7	Ag Pb_{18} $SbTe_{20}$	Bulk	84
	8	SiGe	Bulk	679
	9	$Si_{80}Ge_{20}$	Nanobulk	371
	10	SiGe	Nanowire	679
Silicides	11	$Mg_2Si_{0.85}Bi_{015}$	Nanobulk	6.67
	12	$Mg_2Si_{0.6}Sn_{0.4}$	Bulk	4.04
	13	Si	Nanobulk	3.09
	14	Si	Nanowire	3.09
	15	Mn$Si_{1.75}$	Bulk	1.46
	16	$Mn_{15}Si_{28}$	Nanobulk	1.51
Clathrates	17	$Ba`_8Ga_{16}Ge_{28}Zn_2$	Bulk	615
	18	$Ba_8Ga_{16}Ge_{30}$	Bulk	644
	19	$Ba_7Sr_1Al_{16}Si_{30}$	Bulk	1.64
Skutterudites	20	CeFe_4Sb_{12}	Bulk	37
	21	$Yb_{0.2}In_{0.2}Co_4Sb_{12}$	Bulk	24
	22	$Ca_{0.18}Co_{3.97}Ni_{0.03}Sb_{12.40}$	Bulk	13
Oxides	23	$(Zn_{0.98}Al_{0.02})O$	Bulk	2.30
	24	$Ca_{2.4}Bi_{0.3}Na_{0.3}Co_4O_9$	Bulk	30
	25	InGaZnO	Nanowire	511
	26	$Na_{0.7}CoO_{2-\delta}$	Bulk	36
Half Heuslers	27	$Zr_{0.25}Hf_{0.25}Ti_{0.5}NiSn_{0.994}Sb_{0.006}$	Bulk	9.71
	28	$Zr_{0.5}Hf_{0.5}Ni_{0.8}Pd_{0.2}Sn_{0.99}Sb_{0.01}$	Bulk	8.51
	29	$Ti_{0.8}Hf_{0.2}NiSn$	Bulk	10.70
Other	30	PEDOT:PSS	Polymer	0.34

VI. CONCLUSION

In this study has been classified thermoelectric application in two main parts engine and human application. The voltage generated from thermoelectric generator as a result of heat harvesting from engine application is more than that generated as a result of heat harvesting from human body application. Usually thermoelectric generator used in medical application which is need low power. The result from this review the thermoelectric application could be classified based on average power which generated:

- Low power generated: like human body application this small power enough to utilized in medical devices or watch battery or employment hot water across pipes to convert waste heat into electricity in electronic chip which us in control systems.
- High power generated: like industries applications and internal combustion engines which have high waste heat so the power generated is acceptable result.

As a result of development of material technology the thermoelectric promising perfect future.

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