Performance Analysis of (Bi_2Te_3-PbTe) Hybrid Thermoelectric Generator

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ABSTRACT

The performance of (Bi_2Te_3-PbTe) hybrid thermoelectric generator (TEG) composed of n-type Bismuth Telluride and p-type Lead Telluride semiconductor materials is presented in this paper. The effect of different performance parameters such as output voltage, output current, output power, maximum power output, open circuit voltage, Seebeck co-efficient, electrical resistance, thermal conductance, figure of merit, efficiency, heat absorbed and heat removed based on maximum conversion and power efficiency have been theoretically analyzed by varying the hot side temperature of the hybrid thermoelectric generator up to 350°C and by varying the cold side temperature from 30°C to 150°C. The results showed that a maximum power output of 21.7 W has been obtained with the use of one hybrid thermoelectric module for a temperature difference of 320°C between the hot and cold side of the thermoelectric generator at matched load resistance. The figure of merit was found to be around 1.28 which makes its usage possible in the intermediate temperature (250°C to 350°C) applications such as heating of Biomass waste, heat from Biomass cook stoves or waste heat recovery etc. It is also observed that the hybrid thermoelectric generator offers superior performance over 250°C of the hot side temperature, compared to standard Bi_2Te_3 modules.

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1. INTRODUCTION

The non-renewable energy resources account for 85% of world's energy fuels [1]. They are not only used for power generation, but also for domestic needs, transportation purposes and so on. Hence they are getting depleted at a faster rate [2]. As proposed by the International Energy Agency Policies, only 20% of the non-renewable energy resources will be available for electric power generation by the year 2050. Hence, the world's electricity supply needs to be flipped from 68% fossil fuels to 65% renewable energy sources [3]. Power generated using Biomass resources are very less and hence much research is needed to explore the possibilities of increasing the electric power production by utilizing the available resources effectively. This renewable energy can also be termed as green or clean energy [4] as it results in less carbon emission [5], thereby reducing green house gas emissions [6], [7] and hence, reduced effects of global warming [8]. The use of biomass waste heat is proposed to be an effective method for power generation. For small-scale power production, thermoelectric generators (TEG's) evolve as a promising source of technology [9]. Thermoelectric generators are solid-state semiconductor devices which can convert direct heat to electrical power [10]. The major advantage of these devices is that the heat does not have to be of higher grade to be converted; thus, they can be used to recover the energy that is rejected as waste heat to the atmosphere. They provide a long term passive solution to produce electricity from waste heat obtained from any process. The benefits of the TE technology over others – no moving parts, high reliability, low maintenance, competitive price, long life, easy installation, continuous operation, quiet and environmental friendly [11,12]. One significant disadvantage of the TEG's is the lovw thermoelectric conversion efficiency. However, this will no longer be a major issue because of its low generation cost or even, no cost [13], [14].

Many researchers have investigated the methods of effective production of electrical power from various sources of harvested waste heat using thermoelectric generators. The summary of the findings are discussed below:

Liu et al. [4], experimentally compared different semiconductor materials and concluded that a Bi2Te3 semiconductor with less insulator plate thickness was considered to be economically feasible with highest power cost ratio. A model was proposed to generate 500W of electrical power. The cost of TEG system was lower than those of PV and wind power systems. Shaughnessy et al. [15] integrated a thermoelectric generator with a cooking stove. These generator units are practically deployed in a village in Malawi. It provides the user with the ability to charge LED lights. Wu et al. [16] made a theoretical analysis with a warm waste heat source given directly to a thermoelectric generator. Champier et al. [17] concluded that the output power of the thermoelectric module depends mainly upon the pressure applied on the modules connected in series. Gou et al. [18] employed 10 series connected Peltier modules and found that the output power obtained was not even sufficient to drive the axial fan used for cooling purposes.

Kinsella et al. [19] developed a prototype electrical generator for delivering small amounts of electricity. It was concluded that higher the temperature difference, higher the obtained power output. Hsu et al. [20] concluded that for any type of TEG employed, the output increases depending upon the clamping force in addition to maximum permissible temperature gradient. It was also suggested that the clamping force should not exceed 18 kgW, else the TEG module will get damaged. Xiao et al. [21] used a multi-stage module with two layers of skutterides placed above the Bi2Te3 module and concentrated solar radiation as heat source. It was proved that the output doubled when a 3-stage module was employed.

Chen et al. [22] compared a Peltier module and a Seebeck module and concluded that 4 Peltier modules connected in series produced more power than a single Seebeck module, thereby the Peltier module being cost effective for power generation. Nuwayhid et al. [23] compared the performance of three TEG's and redesigned the TEG having low cost-power ratio to get an enhanced power output. Van sark [24] used a very low temperature thermoelectric module for power generation. A TEG was attached to the backside of the PV module. The power output depends upon the irradiance value.

It was clearly observed from the above mentioned literature that, most of the researchers' have used only Bi2Te3 modules for power generation. Also the power generation rate increases with the increase in the temperature difference between the hot and cold junction and the clamping force of the thermoelectric generator. It was also observed that the Bi2Te3 thermoelectric generator can be used for only low temperature applications with the temperature gradient of upto 250^{o}C. The PbTe thermoelectric generator can only be used for high temperature applications, with the temperature difference greater than 350^{o}C. Most of the biomass waste heat temperature ranges between 150^{o}C and 350^{o}C. The use of hybrid thermoelectric generator composed of n-type Bismuth Telluride and p-type Lead Telluride with the operating temperatures ranging from 100^{o}C to 350^{o}C has not been studied so far. Therefore, in the present study an attempt is made to analyze the performance of hybrid thermoelectric power module (TEG1-PB-12611-6.0), supplied by Thermal Electronics Corporation, Canada. It is designed as an intermediate thermoelectric module with high temperature bonding materials that allow them to withstand temperatures upto 350^{o}C continuously and intermittently upto 380^{o}C. The effect of various performance parameters such as voltage, current, output power, heat supplied and heat absorbed at maximum power and conversion efficiency by varying the hot side temperature from 80^{o}C up to 350^{o}C and varying the cold side temperature from 30^{o}C to 150^{o}C of the hybrid thermoelectric generator, at different load conditions has been analyzed.

2. ONE-DIMENSIONAL STEADY STATE ANALYSIS

Thermoelectric generators are solid-state semiconductor devices that can convert direct heat into electrical power as long as the hot side is at a higher temperature than the cold side. The thermoelectric effect includes three individually identified effects: the Seebeck effect, Peltier effect and Thomson effect. A typical thermoelectric module consists of a large number of n-type and p-type pellets connected together by a metal plate through soldering. Conversion of temperature difference directly into electricity is termed as "Seebeck effect". When current flows through a junction between two conductors, heat is either generated or removed at the junction. This is termed as "Peltier effect". The heating or cooling effect of a current carrying conductor with a temperature gradient is described by the "Thomson effect". The TEG working principle is based on the thermoelectric effect. The working principle of a single TEG couple is depicted in Figure 1.

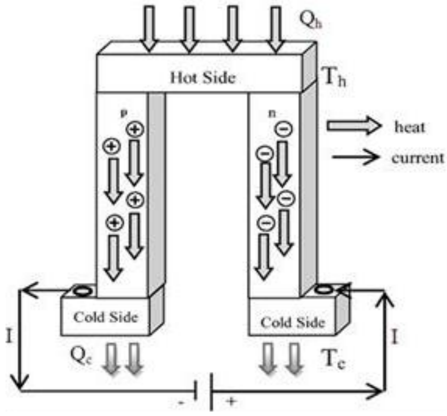

Figure 1. Schematic of a single thermoelectric couple

The material's thermoelectric properties such as – electric resistance, thermal conductance and Seebeck co-efficient vary depending upon the manufacturing processes. When an external heat Q_h (W) is applied over the hot side to create a temperature gradient, ΔT (ºC) between the hot and cold sides, an electrical current I (A) is induced in the circuit. This is given in terms of 'Seebeck effect'.

According to Zhang et al. [25] it is difficult to obtain the module parameters electric resistance - R_m, thermal conductance - K_m and Seebeck co-efficient – α from the TEG manufacturers as they are prone to protect their manufacturing materials and processes. The module parameters R_m, K_m can be obtained from TEG module operating parameters. The following equations (1), (2) and (3) correlate the module parameters R_m, K_m and α with the TEG specifications data sheet.

$$R_m = \frac{(T_h - \Delta T_{max})V_{max}}{T_h I_{max}} \tag{1}$$

$$K_m = \frac{(T_h - \Delta T_{max})V_{max} I_{max}}{2 T_h \Delta T_{max}} \tag{2}$$

Where, ΔT_{max} is the largest temperature difference between the hot and cold sides of the ceramic plates at a particular hot side temperature T_{ho}, I_{max} is the current that can produce maximum ΔT_{max} across the module and V_{max} is the DC voltage at the temperature difference of ΔT_{max}. The Seebeck co-efficient, α as given in equation (3), is defined as the ratio of the open circuit voltage, V_{oc} (can be obtained from the product specification) to the difference in temperature between the hot and cold sides of the ceramic plates, $\Delta T = T_h - T_c$. Its unit is in terms of $\mu V/K$..

$$\alpha = \frac{V_{OC}}{\Delta T} = \frac{V_{oc}}{T_h - T_c} \tag{3}$$

The figure of merit, Z denotes the ability of a material to effectively produce thermoelectric power. From equations (1), (2) and (3), the TEG Z-factor is given by,

$$Z = \frac{\alpha^2}{R_m K_m} \tag{4}$$

The above equations are proposed for a thermoelectric cooler. But, since the thermoelectric cooler and the generator have the same thermoelectric material properties, they can be applied for TEG parameter analysis also [14]. The value of load resistance, R_L can be calculated using equations (1) and (4) which will be used to find the value of current.

$$R_L = R\sqrt{1+ZT_{avg}} \tag{5}$$

where, ZT_{avg} is given by the product of the figure of merit Z and the average value of the hot and cold side temperatures respectively,

$$ZT_{avg} = \frac{Z(T_h + T_c)}{2} \tag{6}$$

The current, I through the circuit is calculated using equation (6) as given below,

$$I = \frac{\alpha \Delta T}{R_L + R} \tag{7}$$

Where, Ω is defined as the Seebeck co-efficient, ΔT is the difference in temperature between the hot and cold sides, (T_h-T_c), R_L is the load resistance and R is the internal resistance. The voltage across the load and the electrical power output can be obtained using the equations (7) and (8) as,

$$V = \alpha \Delta T - IR \tag{8}$$

$$P_{elect} = \left(\frac{\alpha \Delta T}{R_L + R}\right)^2 R_L \tag{9}$$

The conversion efficiency is calculated using equation (9) as,

$$\eta_{mc} = \eta_{ca}\left(\frac{\sqrt{1+ZT_{avg}}-1}{\sqrt{1+ZT_{avg}}+\frac{T_c}{T_h}}\right) \tag{10}$$

The power efficiency is calculated using equation (10) as,

$$\eta_{mp} = \eta_{ca}\frac{ZT_{avg}}{2+2\frac{T_c}{T_h}+2ZT_{avg}-0.5\eta_{ca}ZT_{avg}} \tag{11}$$

Where, η_{ca} is termed as the Carnot efficiency given by T_c/T_h. It denotes the maximum efficiency limit a heat engine can attain. It mainly depends on the hot and cold side temperatures.

Using the above mentioned design equations, a parametric analysis has been carried out to analyze the performance parameters such as output power, voltage, current, Seebeck co-efficient, electrical resistance, thermal conductance, heat absorbed and heat removed for different loading conditions based on maximum conversion and power efficiency. The afore mentioned parameters are exactly analyzed by developing a MATLAB program and based on the obtained results various characteristic curves are drawn and discussed in the following sections.

3. PERFORMANCE EVALUATION

A hybrid thermoelectric power module (TEG1-PB-12611-6.0), composed of n-type Bismuth Telluride and p-type Lead Telluride semiconductor material supplied by Thermal Electronics Corporation, Canada is considered for the analysis. The module parameters are listed in Table 1. The main parameters considered for analysis include output voltage, output current, output power, maximum power output, open circuit voltage, Seebeck co-efficient, electrical resistance, thermal conductance, figure of merit, efficiency, heat absorbed and heat removed based on maximum conversion and power efficiency. If the temperature gradient across the thermoelectric module is higher, the electrical output will be higher. The load resistance also plays a major role in influencing the output of the thermoelectric module. The thermoelectric module was analyzed for different cold side temperatures with varying hot side temperatures. The load resistance was increased from a minimum upto 15 ohms.

Table 1 TEG1-PB-12611-6.0 Supplier Specifications

Hot side temperature	350˚C
Cold side temperature	30˚C
Open circuit voltage	9.2V
Matched load resistance	0.97 Ω
Matched load output voltage	4.6 V
Matched load output current	4.7 A
Matched load output power	21.7 W
Heat flow across the module	≈ 310 W
Heat flow density	≈ 9.88 W cm^{-2}
AC resistance measured under 27˚C @ 1000 Hz	0.42~0.52
Size	56 mm x 56 mm
Number of couples	126

Various graphs were drawn between output power, output voltage and output current with respect to load resistance for different values of cold side temperature, T_c = 30/50/80/100/150^{o}C as shown if Figures 2, 3 and 4.

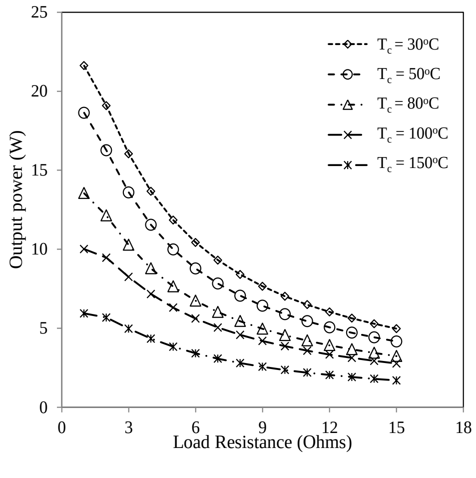

Figure 2. Variation of output power with load resistance for different cold side temperatures

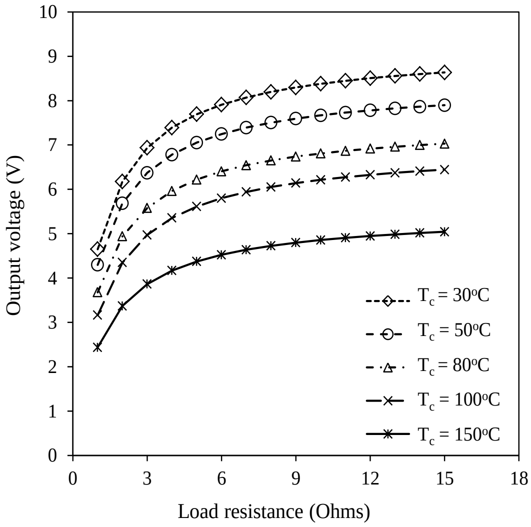

Figure 3. Variation of output voltage with load resistance for different cold side temperatures

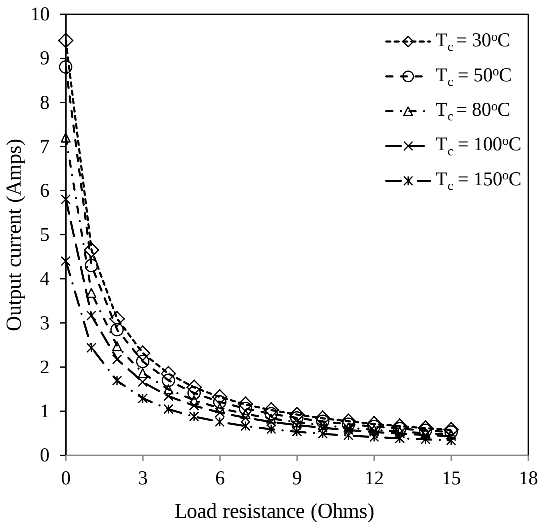

Figure 4. Variation of output current with load resistance for different cold side temperatures

It was found that the thermoelectric module worked efficiently when the cold side temperature was maintained at 30^{o}C with varying hot side temperatures. This is because the output power is directly proportional to square of temperature difference and the load resistance. The maximum output power values at different cold side temperatures at matched load resistance and maximum temperature gradient are given in Table 2. From Figure 2 it is evident that a maximum power output of 21.7 W is obtained only when the cold side temperature is maintained at a minimum, T_c = 30^{o}C. From Figures 3 and 4, it is seen that, at matched load resistance, the output voltage is about 4.6V and the output current is about 4.7A.When T_c is increased beyond 30^{o}C, output power, voltage and current obtained decreases, even at higher values of temperature gradient, ΔT. Hence, it is concluded that for the analysis, the hot side temperature, T_h is varied in steps of 30^{o}C from 80^{o}C to 350^{o}C while the cold side temperature is maintained constant at 30^{o}C for different loading conditions.

Table 2 Output Power at Different Cold Side Temperatures

Cold side temperature Tc (°C)	Maximum temperature gradient, ΔT_{max} (°C)	Matched load resistance R_L (ohms)	Output power (Watts)
30	320	0.97	21.62
50	300	0.94	18.65
80	270	1.02	13.54
100	250	1.2	10
150	200	1.24	6

From Equation (8), the output power can be obtained. The variation of output power as a function of electrical load for different values of temperature gradient (ΔT) at a constant cold side temperature (Tc =30°C), is given in Figure 5. It is evident that the predicted output power performance increases with the corresponding increase in temperature difference. Thus we can prove that power is proportional to square of the temperature difference, ΔT^2 and works best when the temperature gradient is maintained at 320°C. Hence, it is concluded that the power increases in an exponential trend and is maximum at a maximum difference in temperature between the hot and cold sides of the ceramic plates. A maximum of 21.7W is obtained when the hot side temperature is at 350°C while the cold side temperature is maintained constant at 30°C.

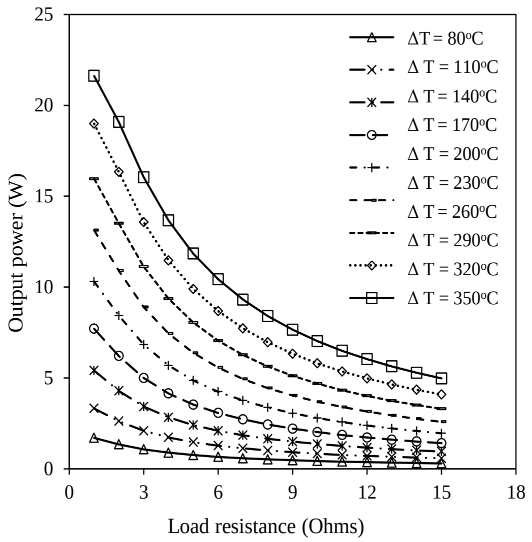

Figure 5. Variation of output power with load resistance for different temperature gradients

The plot between the output voltage and output current for various hot side temperatures is shown in Figure 6. It is clear that there exists a linear relationship between the voltage and current. From Figure 6, the "effective" open circuit voltage for each value of ΔT can be obtained by extrapolating the voltage values corresponding to zero current at the y-axis intercept. The slope of each line represents the internal electrical resistance of the module at some particular measuring environment and each interception of the y-axis at zero current (I=0) gives the open circuit voltage. Figure 7 gives the plot between open circuit voltage and the temperature difference. It is seen that the open circuit voltage of the system increases with an increase in the hot side temperature in a linear trend.

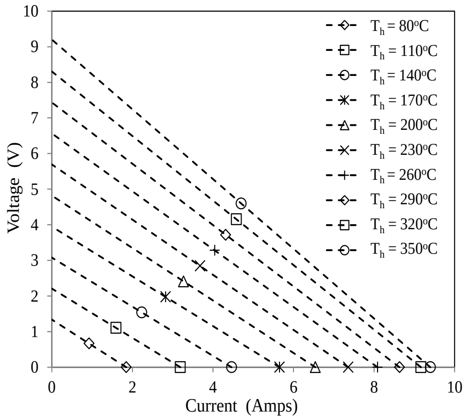

Figure 6. Variation of voltage with respect to current

According to electrical circuit theory, maximum output is reached when the electrical load resistance matches with the internal electrical resistance of the thermoelectric module. Hence, substituting $R_L = R$ in Equation (6), (7) and (8), the equations are reduced to obtain the maximum performance parameters as follows:

$$I_{max} = \frac{\alpha \, \Delta T}{2R} \tag{11}$$

$$V_{max} = \frac{\alpha \, \Delta T}{2} \tag{12}$$

$$P_{max} = \frac{(\alpha \, \Delta T)^2}{4R} \tag{13}$$

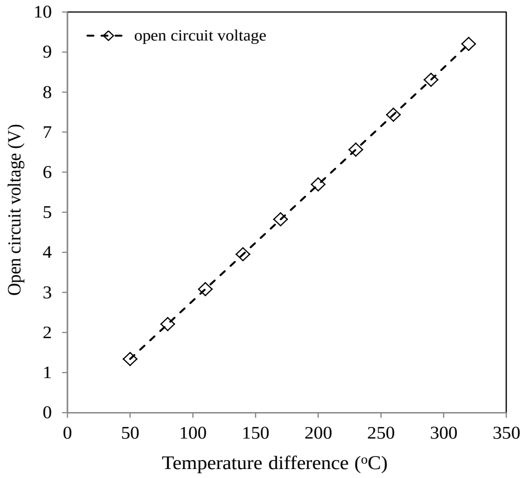

Figure 7. Variation of open circuit voltage with respect to temperature gradient

Figure 8 gives the maximum attainable output power and load voltage characteristics as a function of output voltage and open circuit voltage. From Figure 8 it is apparent that the maximum power output increases with an increase in voltage in a polynomial trend.

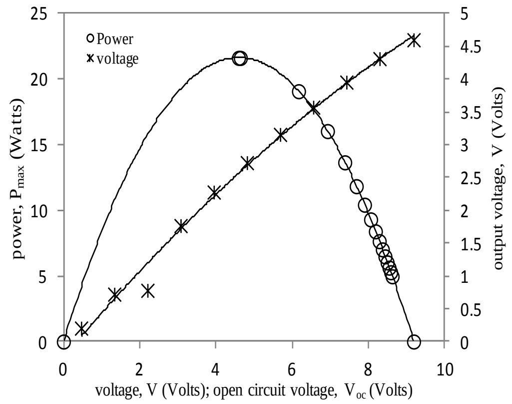

Figure 8. Variation of output power and load voltage with respect to open circuit voltage

Power is proportional to square of the temperature difference, ΔT^2 and square of Seebeck co-efficient, α^2. An increase in temperature difference should have a corresponding compensating decrease in Seebeck co-efficient. But the compensation is very small for this corresponding increase. Hence, any change in temperature difference will have a direct influence on the delivered electrical power output. It also clearly indicates that maximum power can be obtained from the thermoelectric module when the load voltage equals half the open circuit voltage. In order to calculate the Seebeck co-efficient, a method proposed by Hsu et.al [20] is employed. The proposed "effective" Seebeck co-efficient model is used to calculate the "effective" Seebeck co-efficient under actual load conditions. According to Hsu et al. [20], the relationship between voltage and current is given by Equation (7) , ($V = \alpha\ \Delta T\text{-}IR$). At zero current (I=0), the voltage becomes maximum which equals the open circuit voltage. Hence the term $\alpha\Delta T$ becomes maximum in which "α" can be defined as the "effective" Seebeck co-efficient, α_{eff}. Due to the above condition, Equation (7) reduces to

$$\alpha = \frac{V_{oc}}{\Delta T} \qquad (14)$$

The "effective" Seebeck co-efficient indicates the actual behavior of the thermoelectric generator system under different load conditions, neglecting the thermal and electrical contact resistances. Rowe and Min [26] developed a theoretical model to calculate the Seebeck co-efficient taking into account the thermal and electrical contact resistances between the ceramic plates. But, this theoretical model requires thorough information of the physical properties of the p-n pellets in the thermoelectric module – detail that is not easily and at all times available from the manufacturer or supplier. Hence the approach "effective Seebeck co-efficient model" proposed by Hsu et al. [20] has been employed. Figure 9 showing the effective Seebeck co-efficient, consistent with Equation (14), is thus realized at a particular hot side temperature. From the graph, it is seen that for every increase in temperature gradient, there is only a small corresponding compensating decrease in Seebeck co-efficient.

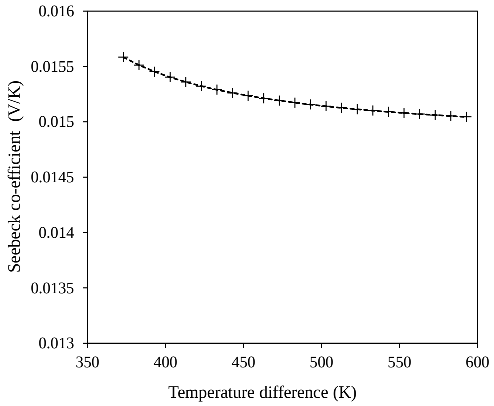

Figure 9. Variation of Seebeck coefficient with respect to temperature gradient

Figure 10 shows the thermal conductance and electrical resistance of the module with respect to the electrical power output characteristics of the thermoelectric generator system.

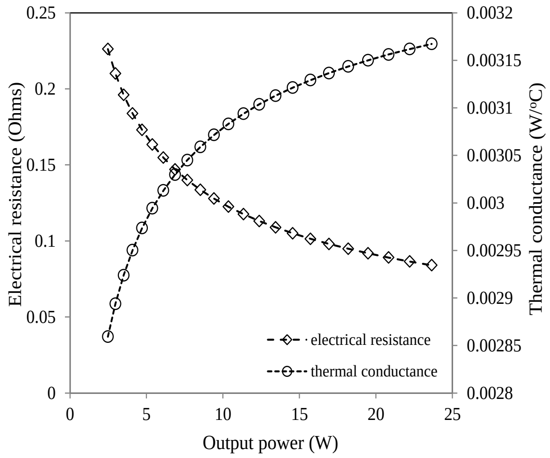

Figure 10. Variation of electrical resistance and thermal conductance with output power

As the temperature gradient across the system increases, heat absorbed by the module increases and hence an increase in output power is achieved. From the graph, it is evident that there is a decrease in the electrical resistance of the module which leads to an increase in the obtained output power. Also, the thermal conductance of the module increases which aids in increasing the output power. Hence, the obtained electrical power output is higher when the heat input to the system is also higher. In Figure 1, Q_h and Q_c represents the heat supplied to the generator from the high temperature reservoir and heat absorbed by the low temperature reservoir. On account of thermal resistance present between the reservoirs and the thermoelectric generator, heat exchange rate is limited. The rate of heat supply, Q_h and heat removal, Q_c is estimated as:

$$Q_h = \alpha I T_h + \frac{R_m I^2}{2} - K_m \Delta T \tag{15}$$

$$Q_c = \alpha I T_c + \frac{R_m I^2}{2} - K_m \Delta T \tag{16}$$

Where α, K_m and R_m are denoted as effective Seebeck co-efficient, module thermal conductance and electric resistance, respectively. In Equation (15) and (16), the terms refer to the heat associated with the Peltier effect, half of Joule heating and Fourier law of thermal conduction. When the thermoelectric generator is subjected to a load, current flows through the circuit. Hence, the Peltier effect is being observed. By applying an energy balance to the thermoelectric module, and neglecting the effects of Joule heating and thermal conduction, Equation (15) and (16) reduces to first term alone. The electrical power output is given as the difference between heat absorption and heat removal from the system, (Q_h - Q_c).

$$P_{elect} = Q_h - Q_c \tag{17}$$

Depending upon the current flowing through the circuit and the junction temperature, the Peltier effect varies and hence the output power produced. The variation of Peltier effect with respect to the current flowing through the circuit is shown in Figure 11. Higher the current flow, more prevalent the Peltier effect.

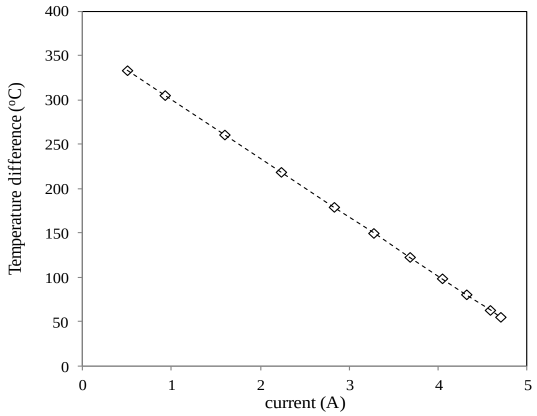

Figure 11. Variation of temperature difference with respect to output current

The performance of a thermoelectric material is measured by the figure of merit, Z. It gives the ability of the thermoelectric material to efficiently produce thermoelectric power. It explains how effectively the thermoelectric generator will work. For good thermoelectric materials, the dimensionless figure of merit, ZT_{avg} is equal to or higher than unity [27]. The most widely used thermoelectric material, for low temperature applications (upto 250^oC) has a maximum ZT_{avg} value of unity [28]. Lead telluride, used mainly for high temperature applications because of its high temperature thermoelectric behavior, has a maximum ZT_{avg} value of 1.4 [28]. The only commercially available Hybrid Thermoelectric generator module, composed of n-type Bismuth Telluride and p-type Lead telluride semiconductor materials, which can operate in the intermediate temperature range of 250^oC to 350^oC was found to have a maximum ZT_{avg} value of 1.28, on analysis. Also, the maximum conversion efficiency and maximum power conversion efficiency was found to be 0.131 and 0.126.

4. CONCLUSION

The most easily and commonly available TEG's for low temperature applications upto 250^o C are Bismuth Telluride based. For temperatures above 350^o C, lead Telluride based TEG's are preferred. The only commercially available Hybrid Thermoelectric generator that can operate upto 350^oC, composed of n-type Bismuth Telluride and p-type Lead Telluride semiconductor materials, supplied by Thermal Electronics Corp., Canada is considered for study and the various electrical performance parameters theoretically analyzed. According to the present study, the following conclusions are arrived:

a. A maximum power output of 21.7W has been obtained with an output voltage of 4.6V and an output current of 4.7A, with the use of a single Hybrid Thermoelectric module, when the hot side is maintained at a maximum allowable temperature of 350^oC and the cold side is maintained at a minimum temperature of 30^oC.
b. The dimensionless figure of merit was found to be 1.28. The maximum conversion efficiency and maximum power conversion efficiency was found to be 0.131 and 0.126.
c. Higher the current, more prevalent the Peltier effect.
d. Based on the analysis and on comparison with an ordinary Bi_2Te_3 module, it is clear that, in general, the hybrid TEG offers superior performance above 250^oC of the hot side temperature when compared with other Bismuth Telluride based thermoelectric generator modules.
e. Hence, it is suggested that the hybrid TEG can be employed in power generation systems that can be operated at a temperature ranging from 250^oC to350^oC, by employing in the places where electrification is not/less possible such as rural or developing areas and also in places with frequent power cuts.

Nomenclature

I	current (A)
K_m	thermal conductance of TEG module (W/ ^oC)
P_{elect}	output power (W)
R	internal resistance (ohm)
R_L	load resistance (ohm)
R_m	electrical resistance of TEG module (ohm)

T temperature (^oC or K)
V voltage (V)
Z figure of merit (1/K)
ZT_{avg} dimensionless figure of merit

Greek Letters
ΔT TEG hot side to cold side temperature difference (^oC or K)
ΔT_{max} largest temperature difference between hot side and cold side (^oC or K)
α Seebeck co-efficient (V/K)
η efficiency

Subscript
avg average of two quantities
c TEG cold side
ca carnot
elect electrical
h TEG hot side
oc open circuit
m TEG module
mc maximum conversion
mp maximum power
max maximum of given quantity

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